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Development of a Moisture Resistant Densified Solid Fuel From Forest Biomass

Renewable Energy Branch

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P-4590/G Final Report

DEVELOPMENT OF A MOISTURE RESISTANT DENSIFIED SOLID FUEL FROM FOREST BIOMASS

EXECUTIVE SUMMARY

The Department of Energy Mines and Resources has contracted a project to Ontario Research Foundation on making improvements to the existing densified biomass products. Improved moisture resistance and increased integrity and strength of the densified biomass were the major objectives of this investigation.

The study consisted of the following main subject areas:

- Literature review,
- Visits to existing production facilities,
- Evaluation of some critical production parameters, particle size, moisture content, and temperature,
- Evaluation of some additives to improve pellet performance with special emphasis on the use of waste products,
- Manufacturing densified pellets at the pilot plant scale with those additives showing the greatest potential on the laboratory scale,
- Measuring pellets on a residential furnace with respect to emissions and efficiency.

The literature review reveals the enormous potential of biomass utilization. In North America, only 5% of the available biomass is currently burned; potentially 25% of Canada's energy needs could be supplied from biomass (assuming 70% conversion efficiency). Of the various methods of densification (baling, rolling, cubing, extrusion, briquetting, pelletization) only extrusion and pelletization appear economically and technically feasible. Economics are determined greatly by the price of raw material (chips, sawdust) for densification and the energy expended in drying and compressing of this feed into the densified fuel. Drying consumes the most energy.

Of the process variables studied, particle size of the feed to the densifying unit was found to be a significant variable. Particles passing the 20 mesh (Tyler) screen showed greater water stability and strength than particles retained on the 8 mesh screen.

Chips pressed at 19% moisture were stronger than those pressed at 30% moisture, but the latter ones showed greater water stability.

Temperature of the pressing unit in the range of 130°C to 170°C showed that pellet density, strength, and moisture stability all increased as press temperatures increased.

Moisture resistance was defined as less than 10% dimensional change after 24 hours soaking in water at room temperature. Taking this strict definition of moisture resistance, virtually all pellets produced without additives failed this test, whereas in a previous study (Enfor C-97), it was reported that water stable pellets were made at 150°C temperature, 27 MPa pressure and 15% moisture content of the feed, but water stability was not strictly defined and measured.

Some of the additives studied provided excellent water stability to the laboratory formed pellets. The following materials were evaluated:

- Polyethylene powder and waste polyethylene film
- Crude tall oil rosin - Tall oil pitch
- Coal tar pitch (core pitch)
- Petroleum vacuum residue
- Pine tar binder
- Waxed corrugated fibreboard

The addition rate ranged from 2 - 5% based on moist (30% MC) wood weight with the above materials.

Water stability was achieved with the following additives:

Additive	Addition Level % Wet Wood	Press Temp. ^{o}C	% Change In Thickness
Polyethylene Powder	5	160	4.8
		170	4.5
Polyethylene Film	2.26	170	9.8
	3.5	160	9.3
		170	4.9
	5.1	160	9.0
		170	5.8
Tall Oil Pitch	2	170	9.3
Core Pitch	2	170	9.5
	5	170	7.1

Corrugated waxed paper, Petroleum vacuum residue and Pine tar binder failed to provide water stability. With respect to strength improvement, waxed corrugated paper, polyethylene powder, Pine tar blend and Tall oil pitch reduced pellet strength and the other four additives all improved pellet performance.

Based on the laboratory work on additives, it was concluded that polyethylene at the 2 - 5% addition level showed the greatest commercial potential. Availability, price and ease of addition to the system, were all considered in the selection.

About 75 Kg of commercial pellets were produced by Shell Canada from:

100% Jack pine wood,
98% Jack pine 2% polyethylene,
95% Jack pine 5% polyethylene.

These pellets were evaluated for: energy content; moisture and ash content; density; pellet strength; and water resistance.

The pellets containing polyethylene had a higher heating value (2 - 5%) and the same moisture and ash content as those pellets made from 100% Jack pine. The densities were lower for the pellets made with polyethylene.

On shaking, the experimental pellets made with polyethylene lost less weight than the control pellets made from 100% Jack pine. Water stability on soaking was not significantly improved over that for a commercially available Energex pellet. This is ascribed to the short duration of the pilot scale production, and less than optimum manufacturing conditions.

In the combustion tests compared with the commercial Energex pellets, the pine pellets were as easy or easier to ignite than the Energex pellets. The total hydrocarbon content of the flue gases was considerably lower for the experimental pellets than for the Energex pellets. There was no significant change in the furnace efficiency for the four pellets tested. The conclusion from the test program was that the combustion characteristics of the experimental fuel pellets were equal, or superior to those of the commercially available Energex fuel pellets in all aspects considered.

Rapport définitif P-4590/G

DÉVELOPPEMENT D'UN COMBUSTIBLE SOLIDE RÉSISTANT À L'HUMIDITÉ PAR DENSIFICATION DE LA BIOMASSE FORESTIÈRE

RÉSUMÉ POUR LA HAUTE DIRECTION

Le ministère de l'Énergie, des Mines et des Ressources a confié à l'Ontario Research Foundation l'exécution d'un projet visant à perfectionner les produits de densification de la biomasse de manière à en abaisser l'absorption d'humidité tout en améliorant leur solidité et leur résistance.

Voici les grands thèmes de l'étude:

- Dépouiller la documentation.
- Visiter les installations de production existantes.
- Évaluer certains paramètres décisifs de production, la granulométrie, la teneur en humidité et la température.
- Évaluer certains additifs en vue d'améliorer le rendement des granulés, en cherchant surtout à réutiliser les déchets.
- Fabriquer des granulés densifiés dans une usine pilote à partir des additifs qui se sont avérés les plus prometteurs en laboratoire.
- Mesurer les granulés brûlés dans une chaudière résidentielle afin d'en connaître les émanations et l'efficacité.

Le dépouillement de la documentation a révélé d'énormes possibilités d'utilisation de la biomasse. En Amérique du Nord, 5% seulement de cette ressource sont actuellement brûlés, alors qu'elle pourrait éventuellement répondre à 25% des besoins énergétiques du Canada (en supposant une conversion efficace à 70%). Parmi les diverses méthodes de densification (mise en balle, en rouleau, en cube, extrusion, agglomération, granulation), seules l'extrusion et la granulation semblent économiques et techniquement réalisables. La rentabilité est largement fonction du prix de la matière brute (copeaux, bran de scie) et de l'énergie consommée au séchage et au compressage de cette matière brute pour en faire un combustible densifié. L'étape du séchage est la plus énergivore.

Parmi les variables du procédé qui ont été étudiées, la granulométrie des matières de charge de l'unité de densification était la plus importante. Les granules faits de particules traversant un crible de 20 mailles (type Tyler) avaient la plus grande stabilité à l'eau et étaient plus résistants que ceux dont les particules étaient retenues par un crible de 8 mailles.

Les copeaux pressés de sorte qu'ils ne contiennent plus que 19% d'humidité sont plus résistants que ceux qui en contiennent 30%, bien que ces derniers aient une plus grande stabilité à l'eau.

Entre 130 et 170°C, la densité, la résistance et la stabilité à l'humidité des granulés croîssent proportionnellement avec la température de la presse.

La stabilité à l'humidité a été définie comme une variation dimensionnelle de moins de 10% lorsque le produit trempe dans l'eau pendant 24 heures, à la température de la pièce. Étant donné la rigueur de cette définition, virtuellement tous les granulés produits auxquels on n'avait rien ajouté ont échoué à l'essai, tandis qu'une étude antérieure (Enfor C-97), signalait que des granulés stables à l'eau avaient été fabriqués à 150°C, à une pression de 27 MPa, la matière brute contenant 15% d'humidité; cependant, la stabilité à l'eau n'avait pas été définie et mesurée avec rigueur.

Certains des additifs étudiés fournissaient une excellente stabilité à l'eau aux granulés formés en laboratoire. Voici les matériaux évalués:

- Polyéthylène pulvérulent et pellicules de déchets de polyéthylène
- Tallol brut - poix de tallol
- Brai de goudron de houille (core pitch, soit du brai de goudron extrêmement pur)
- Résidu de raffinage de pétrole
- Liant au goudron de pin
- Carton ondulé et ciré

Le taux d'addition variait entre 2 et 5%, selon la masse du bois humide (30% d'humidité).

La stabilité à l'eau a été réalisée au moyen des additifs suivants:

Additif	Addition % humidité du bois	Température de la presse °C	Variation de de l'épaisseur en %
Polyéthylène pulvérulent	5	160	4,8
		170	4,5
Pellicule de polyéthylène	2,26	170	9,8
	3,5	160	9,3
		170	4,9
	5,1	160	9,0
		170	5.8
Brai de goudron	2	170	9,3
Brai de houille	2	170	9,5
	5	170	7,1

Le carton ondulé et ciré, le résidu de raffinage et le liant au goudron de pin n'ont pas conféré de stabilité à l'eau. Le carton ondulé le polyéthylène pulvérulent, le mélange de goudron de pin et le brai de goudron de houille ont diminué la résistance des granules tandis que les quatre autres additifs l'ont améliorée.

À la lumière des travaux effectués en laboratoire sur les additifs, il a été conclu que l'addition de 2 à 5% de polyéthylène semblait le mélange le plus prometteur sur le plan commercial. La disponibilité et le prix de l'additif ainsi que sa facilité d'addition dans le procédé ont tous été pris en considération.

Shell Canada a produit environ 75 kilogrammes de granulés commerciaux à partir de:

100% de pin gris
98% de pin gris additionné de 2% de polyéthylène
95% de pin gris additionné de 5% de ployéthylène

On a évalué la valeur énergétique, la teneur en humitité et en cendres, la densité, la résistance et l'imperméabilité de ces granulés.

Ceux qui renfermaient du polyéthylène avaient un pouvoir calorifique plus élevé (de 2 à 5%) et la même teneur en humidité et en cendres que les granulés faits seulement de pin gris. Par contre, leur densité était inférieure.

A l'agitation, les granulés expérimentaux faits de polyéthylène perdent moins de masse que les granulés de contrôle faits de pin gris uniquement. La stabilité à l'eau lorsque ces produits sont trempés ne s'améliore pas beaucoup par rapport à celle du granulé commercial Energex. Ce phénomène s'explique par la courte durée de la production à l'échelle pilote et par des conditions de fabrication moins qu'optimales.

Lors des essais de combusion, les granulés de pin s'allument facilement, du moins plus facilement que les granulés commerciaux Energex.

Par ailleurs, ces granulés expérimentaux dégagent des fumées contenant beaucoup moins d'hydrocarbures que les granulés Energex. Le rendement de la chaudière ne variait pas sensiblement, quel que soit la type de granulés utilisés. Il faut donc conclure du programme d'essai que les caractéristiques comburantes des granulés expérimentaux étaient à tous les égards égales ou supérieures à celles des granulés commerciaux Energex.

SECTION I

DEVELOPMENT OF A MOISTURE RESISTANT DENSIFIED SOLID FUEL FROM FOREST BIOMASS

LITERATURE REVIEW

ABSTRACT

The molecular specific gravity of forest biomass is about 1.5: but in its natural form it is often bulky, wet, dispersed, heterogeneous and biodegradable. Densification eliminates most of these problems while enhancing the utility of biomass for energy and chemical feedstocks. Densified biomass is uniform, clean and stable; its storage, transportation and combustion are efficient. It can be burned in standard boilers efficiently with low particulate emission.

Biomass densification may be achieved by baling, roll-compressing, pelleting, cubing, briquetting and extrusion. Baling and roll-compressing only generate moderate compaction, and are more suitable for the collection, handling and transportation of agricultural biomass and certain types of forest biomass (e.g., "mini-rotation" crops, logging residues). Pelleting, cubing, briquetting and extrusion achieve high compaction, and produce densified biomass with specific gravity of 0.8 - 1.3. The basic process steps are size reduction, drying and densification. Approximately 18% of the energy content in raw biomass is expended in processing; 2% for size reduction, 14% for drying, 2% for densification.

Densification equipment is available from several suppliers in North America, Europe, and Japan; and there are a number of manufacturers of densified biomass fuel in the U.S. and Canada. Their product is used primarily to generate steam and process heat for forest products installations.

There is a need for an efficient mobile densification system. Reliable information is also needed about the economic and technological role of densification in integrated biomass production and utilization systems.

DEVELOPMENT OF A MOISTURE RESISTANT DENSIFIED SOLID FUEL FROM FOREST BIOMASS

1. INTRODUCTION

Increases in the price of conventional forms of energy and in many cases reductions in their availability are now generally understood to be inevitable. This is due to a number of factors:

- the finite nature of most conventional forms of energy
- the inordinate power over oil price of the OPEC cartel, although currently this organization appears to have fallen from power
- the regional and international discrepancies that exist between energy supply and demand
- the potentially serious health and environmental questions regarding the use of nuclear fuels and coal
- the increasing demands being made by Third World countries for fossil fuels as they continue attempts to industrialize
- the increasing demand for all forms of energy in the developed world.

Energy development to meet future demand will be a costly and complex process. No single alternative is foreseen to emerge as an "only solution" to the demand problem. The utilization of biomass for energy and chemical feedstocks is part of the solution.

In Canada, various forms of biomass currently account for approximately 3.5% of the total energy consumption (Love and Overend, 1978). This biomass is primarily recovered from wood waste and spent pulping liquors at pulp mills with a much smaller amount used for residential space heating. Table 1 summarizes the estimates that are available on the quantity of the various types of biomass generated in Canada. As can be seen, even excluding the huge potential offered by dedicated forest or crop energy farms, these sources have a gross energy content of 2.77×10^{18}J (2.62×10^{15}BTU), or almost 25% of Canada's total energy demand if a 70% conversion efficiency is assumed.

In the less developed countries, 72% of the wood that is cut each year is used for fuel (FAO, 1978); by comparison only 5% of the wood cut in North America is used for fuel. Much of the wood that is used in the less developed countries is currently burned inefficiently.

Thus in Canada, as will be the case in most other countries with a sizable forest products industry, a large energy potential exists in the form of harvesting and mill residues and currently unutilized species. Harvesting residues are equal in volume to the actual wood taken away from the forest site. The presence of slash left on a logged site almost completely prevents natural regeneration for a number of years: it is unsightly and also interferes with mechanized planting. In the less developed countries where wood is already used to a large extent for fuel, a large potential exists for upgrading of biomass for use in more efficient stoves or boilers.

In its natural form biomass is often an inefficient fuel because it is bulky, wet and dispersed. Densification can reduce these problems. The purpose of this report is to present an overview of the potential role of densification in biomass utilization. This report is based on a recent survey by the author of the technical and patent literature on densification, and a questionnaire-survey of several North American equipment manufacturers.

Table 1: Estimated Supply of Biomass in Canada by Type and Source

TYPE/SOURCE OF BIOMASS	QUANTITY PRODUCED (10^6 Oven-Dry Tonnes)	GROSS ENERGY CONTENT (10^{18} Joules)
Forest Waste		
- Mill Residues	6.8	0.14
- Residues from Forest Operations	28.1	0.58
Dedicated Forest Biomass		
- Unutilized Trees in Currently Logged Areas	18.1	0.37
- Wood Available in Areas Not Currently Logged	47.2	0.97
- Energy Farms	(*)	(*)
Animal Waste	11.4	0.28
Crop Waste	15.3	0.25
Dedicated Crops	(*)	(*)
Aquatic Biomass	(**)	(**)
Solid Waste	9.6	0.17
Sewage Sludge	0.4	0.01
TOTAL	137.0	2.77

Source: Love and Overend (1978)

(*) No estimate of the potential contribution of agro-forestry crops specially designed for energy production could be made, although it has been hypothesized that the energy available from forest resources may be underestimated by a factor of 3-5.

(**) No estimates available.

2. ADVANTAGES AND DISADVANTAGES OF BIOMASS AS AN ENERGY SOURCE

Biomass has a number of desirable attributes as an energy source. These include:

- ready availability
- renewability
- clean, nearly pollution-free combustion
- low energy and capital requirements for production

On the other hand, raw biomass fuel has several disadvantages. These are:

- relatively low heat value per unit volume
- variability of quality of heat value
- difficulty in controlling the rate of burning
- rapid burning, necessitating frequent refuelling
- difficulty in mechanizing continuous feeding
- large area requirement for storage
- economic problems in transportation and distribution
- subject to bio-deterioration

Several of these undesirable attributes result from the low mass and volume energy density of biomass. The mass energy density (MED) and volume energy density (VED) of biomass are 3 - 4 times less than that for coal or gasoline (Table 2). In bulk form (i.e., pile of wood chips, sawdust or shavings), the biomass densities are even lower due to the "fluff" factor. This results in higher transportation and storage costs as well as lower efficiency of combustion. As with refined petroleum fuels, raw biomass can be upgraded in value for various burning situations. Upgrading may involve one or more of size reduction, drying and densification. Since densification presupposes size reduction and drying (or at least moisture control) subsequent discussion will deal with densification.

Table 2: Energy Densities of Different Fuels by Mass and Volume

Fuel	Moisture Content %	Density g/cm^3	Heat of Combustion MED* (kJ/g)	Heat of Combustion VED** (kJ/cm^3)
1. Biomass	50	1.0	9.2	9.2
	10	0.6	18.6	11.2
2. Densified-biomass	10	1.0	18.6	20.9
	10	1.25	18.6	26.1
3. Charcoal	0	0.25	31.8	8.0
4. Coal (Bituminous)	0	1.3	28.0	36.4
5. Methanol	0	0.79	20.1	15.9
6. Gasoline	0	0.70	44.3	30.9

Source: Reed and Bryant (1978).

* MED: Mass Energy Density

** VED: Volume Energy Density

3. BIOMASS DENSIFICATION PROCESSES

Biomass densification may be defined as compression or compaction to remove inter- and intra- particle voids. Five densification processes are now practiced commercially (Reed and Bryant, 1978); including baling, pelleting, cubing, briquetting and extrusion.

The concept of biomass densification is not new. Briquettes have been manufactured from saw-dust, shavings, bark and other wood residues for the past 75 years. The first U.S. Patent for densification was issued in 1880 (Smith, U.S. Patent No. 233,887). This patent described a process where sawdust and other wood residues were heated to 66°C and subsequently compacted to the density of coal with a steam hammer. Since then several patents were issued on the subject (Edison, S.O. 1902; Mashek, G.J. 1907; Griffin, W.T. 1908; Mulligan, P.C. et al. 1925; Levelton, B.H. 1966; Skendrovic, L. 1970; Beningson, R.M. et al. 1977; Bremer, A.R. 1975; Williams, T.A. 1976; Gunnerman, R.W. 1977; Livingston, A.D. 1977; Johnson, A.O. 1978).

While not precisely explained in the literature, densification is believed to involve compression, deformation and self bonding between adjacent particles of biomass. When heated above the plastic temperature range of 165°C (325°F) wood loses its elasticity and is relatively easily compressed. Particle surfaces come into intimate contact and the thermally softened lignin and other phenolics allow the creation of adhesion between adjacent particles. Moisture plays an important role in densification. It may help in heat transfer and in enhancing the plasticity of the material. If the feedstock is either too dry or too wet pressures required for densification increase dramatically. Normally moisture content should be in the range of 10% - 25%. Gunnerman (1977) in his patent recommends moisture content between 16% and 28%. The pre-heating of feedstock between 50°C and 100°C is usually adequate to soften the lignin. Additional heat is generated from the mechanical work of densification which requires 32 to 80 J/g. With a heat capacity of about 1.7 J/g.°C for wood, this would raise the temperature of the densified material by 20°C to 50°C. Thus in commercial densification systems the densified biomass product emerges with a temperature of about 150°C. The hot biomass is fragile and should be handled carefully until cooled (Reed and Bryant, 1978).

Compression baling and roll-compressing can reduce biomass volume to one-fifth its loose bulk. These processes are useful for agricultural biomass and certain types of forest biomass (e.g., crops from energy plantations, logging residues).

Pelleting employs a hard steel die which is perforated with frequently placed holes 0.3 to 1.3 cm in diameter. The die rotates against inner pressure rollers, forcing the comminuted biomass through the holes with pressures of 7.0 kg/mm^2. As the biomass is extruded through the die, small dense pellets are broken off at specified length (Figure 1). Cubing is a modification of pelleting which produces larger cylinders or cubes, 2.5 to 5.0 cm in diameter.

Briquetting compacts a biomass feedstock between rollers with cavities, producing forms like charcoal briquettes. Extrusion uses a screw extruder to force a feedstock under high pressure into a die thereby forming large cylinders (2.5 to 10 cm) of densified biomass. Binding agents such as paraffin or resin are often added to modify properties of the fuel logs.

A commercial application of the extrusion principle is the "Pres-to Log" machine which had been designed and made by Wood Briquettes Inc., Lewiston, Idaho. This machine manufactures densified fuel from wood waste (sawdust, shavings, etc.) by compressing the material in a primary compression chamber with a feed screw at a pressure of approximately 2.2 kg/mm^2 (3,000 psi). The pressure and friction generate sufficient heat to plasticize wood and create the conditions for self-bonding. The compressed wood material is extruded through cylindrical holes 10 cm (4 inches) in diameter spaced at regular intervals in and extending through the rim of a large wheel. The 10 x 30 cm (4- by 12-inch) briquettes produced by this machine are suitable for hand firing in stoves and fireplaces, but not for mechanical stoking. For stoker briquettes, a different type of machine extrudes the material through a cluster of eight 2.5 cm (one-inch) lengths by rotating knives. These 2.5 cm (one-inch) long pellets are suitable for mechanical stoking. The Taiga extruder is a more recent commercial development (Figure 2).

Several manufacturers and suppliers of equipment are listed in Table 3. Others offer total plant "packages" using equipment from one or more suppliers. One such system is the "Woodex" process (Gunnerman, 1977) of Bio-Solar Corporation. The system is based on hammer mill, dryer and pellet mill. A 108 tonnes-per-day plant has been operating since 1976 in Brownsville, Oregon. Several other plants have been installed recently in the U.S. and Canada. Purchasers of fuel pellets include not only forest products plants but also utilities.

FIGURE 1: THE PELLETING PROCESS

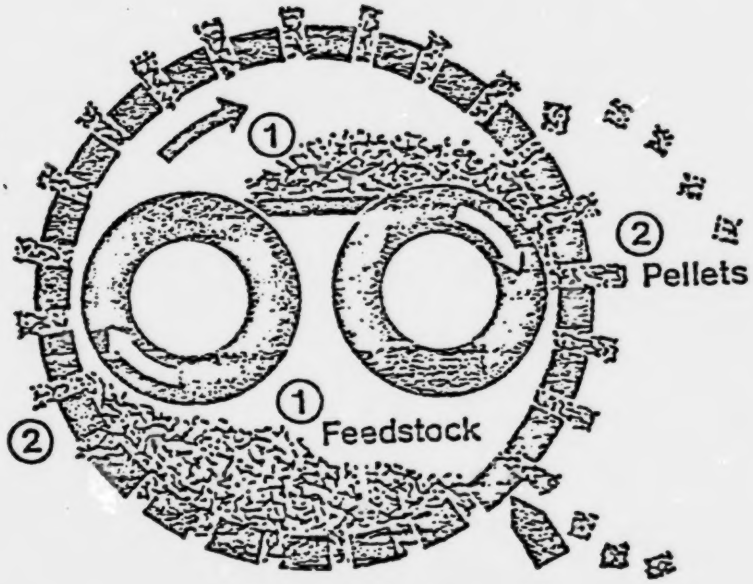
①
②
Pellets
①
Feedstock
②

FIGURE 2: THE TAIGA EXTRUSION PROCESS

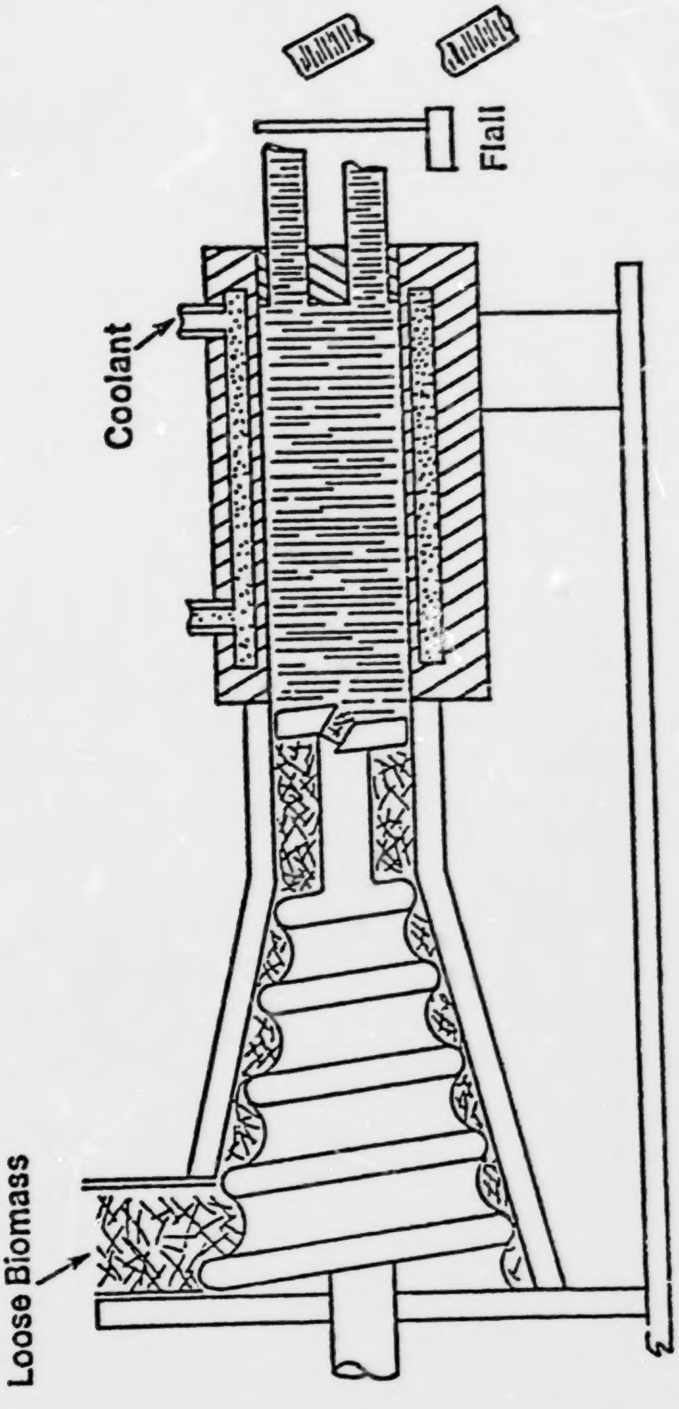
Loose Biomass
Coolant
Flail

Table 3: Some Suppliers of Densification Equipment

	Company	Machine Type
1.	Agnew Environmental Products Inc., Grants Pass, Oregon	Extruder
2.	The Bonnot Co., Kent, Ohio	Extruder
3.	Hawker Siddeley Canada Ltd., Vancouver, British Columbia	Extruder
4.	California Pellet Mill Co., San Francisco, California, and Crawfordsville, Indiana	Pelletizer
5.	Reydco Machinery Co., Redding, California	Extruder
6.	Sprout-Waldron Div. Koppers Company, Inc., Muncy, Pennsylvania	Pelletizer
7.	Taiga Industries, Inc., San Diego, California	Extruder
8.	Columbia Fuel Densification Corp. Phoenix, Arizona	Extruder

4. PROPERTIES AND USES OF DENSIFIED BIOMASS

The specific gravity (or "relative density") of densified biomass is in the 0.8 - 1.3 range, and moisture content is usually 5% to 10%. The bulk density of a pile of pellets is 0.5 - 0.8 g/cm^3. The heat of combustion is around 18.0 - 20.0 kJ/g. Depending on the degree of compaction and the chemical properties of the material, densified biomass usually has improved water-repellency and high resistance to biological deterioration.

It is generally agreed that the principal advantages of densified biomass are:

- rate of combustion is comparable to coal
- permits burning in grate-fired boilers
- provides uniform combustion
- makes transportation, storage and feeding more efficient
- reduces (eliminates?) the possibility of spontaneous combustion in storage
- significant reduction in biodegradability.

While no standardized test procedures have been established for the assessment of the properties and qualities of densified biomass fuel (DBF), some information is becoming available about the properties of commercial DBF. For example, B.J. Levelton and Associates (1981) conducted physical and chemical tests on several commercial DBF products. Among the products tested were Woodex Pellets of Western Energy Corporation of B.C. (Table 4), ROEMMC Pellets of Guaranty Fuels Inc., of Minnesota (Table 5), and "Superfire" Briquettes of Taiga Industries, California (Table 6). Generally it was found that the heating values ranged from about 18.0 to 19.5 kJ/g. Pellet densities were in the range of 1,200 kg/m^3. An important aspect of the tests concerned the loss of fines as a result of a tumble test. Material loss ranged from a low of 2.5% (ROEMMC Pellets) to a high of 10.8% (Woodex Pellets). Percentages were expressed on a weight basis.

Table 4: Physical Characteristics of Woodex Pellets

Pellet Diameter	6.35 mm
Pellet Length	12.7 - 38.1 mm
Pellet Density	1,217 kg/m^3
Bulk Density (dry basis)	567 kg/m^3
Moisture Content (wet basis)	11.2%
Ash Content (dry basis)	1.8%
Heating Value	19,422 kJ/kg Dry
Loss on Tumble Test	10.75 wt %
Pellet Crush Strength	2.0 MPa
Water Stability	No

Table 5: Physical Characteristics of ROEMMC Pellets

Pellet Diameter	9.53 mm
Pellet Length	12.7 - 38.1 mm
Pellet Density	1,181 kg/m^3
Bulk Density (dry basis)	642.3 kg/m^3
Moisture Content (wet basis)	8.9%
Ash Content (dry basis)	3.9%
Heating Value	18,143 kJ/kg Dry
Loss on Tumble Test	2.5 wt %
Pellet Crush Strength	13.4 MPa
Water Stability	No

Table 6: Physical Characteristics of Taiga Briquettes

Pellet Diameter	29.5 mm
Pellet Length	50.8 - 127 mm
Pellet Density	1,217 kg/m^3
Bulk Density (dry basis)	566 kg/m^3
Moisture Content (wet basis)	7.9%
Ash Content (dry basis)	0.92%
Heating Value	19,538 kJ/kg Dry
Loss on Tumble Test	6.0 wt %
Pellet Crush Strength	10.4 MPa
Water Stability	No

Limited tests were also performed by Levelton and Associates on a B.C. Research fuel log. The test results are shown in Table 7. The water stability of the fuel log is classified as marginal because it softens and, when in small sections, will lose most of its structural strength. Pellet-size material would not be suitable for rough transport when wet. Reportedly, prolonged immersion of several of the fuel logs by B.C. Research staff during their test program did not cause any deterioration.

Table 7: Physical Characteristics of B.C. Research Fuel Logs

Log Diameter	78 mm
Log Length	nominally 30.5 mm
Log Density	762 Kg/m^3
Moisture Content (wet basis)	6.0%
Ash Content (dry basis)	0.3%
Heating Value	19,248 kJ/kg Dry
Water Stability	Yes (marginal)

The burning of wood pellets to supplement or replace coal in utility or industrial boilers is well developed. Suspension and spreader stoker coal firing systems can burn densified biomass fuel with little or no modification. Boilers specifically designed to burn wood wastes (small firetube boilers, bark burning boilers, vortex combusters and fluidized bed combusters) can, of course, also burn wood pellets. Such boilers are commonly used to produce steam, process heat or, when coupled to a turbogenerator, electricity.

An advantage in the substitution of pellets for coal is the reduced emissions of sulphur dioxide due to the low sulphur content of the pellets.

Other potential uses of densified biomass fuel include (Reed and Bryant, 1978):

- fueling residential, commercial or industrial central heating systems
- fueling wood stoves
- fueling fireplaces and outdoor grills
- firing external combustion engines
- raw material for pyrolysis and gasification

5. ENERGY BALANCE AND ECONOMICS

The relevance and future role of densification in biomass utilization, in spite of its technical merits, will be determined by the energy balance and production economics of densification systems. The energy required for densification is influenced by the physical attributes of the feedstock (e.g., moisture content, size, type, density, etc.), pellet size, equipment used and other parameters. Approximate energy requirements and feed rates for several kinds of biomass in a 224 kw pellet mill of the California Pellet Mill Company are presented in Table 8. Generally 1 - 3% is needed for size reduction. Feedstock drying requires most of the process energy, ranging from 7 - 15% depending on the initial moisture content of raw biomass. Thus, the energy efficiency of biomass densification is in the range of 82 - 93%.

Currently operating pelletizing plants in Iroquois Falls, Hearst, and Wallenstein, all located in Ontario, use either the dust obtained from the screening of the feedstock or the dust from the screening of the finished pellets for generation of the heat required in the drying of the feedstock. Occasionally off quality pellets are used for feedstock moisture reduction. This practice obviously reduces the energy costs for drying because the required heat is locally generated from waste by-products of the pelletization process.

Reed and Bryant (1978) presented a cost analysis of pelletizing. Cost data was based on the Woodex process of the Bio-Solar Corp.; financial data was based on lumber and paper industry averages. The 272 tonne-per-day Woodex plant in Brownsville, Oregon, cost about $1.25 million, including the cost of classifying, feeding, and cooling equipment; hammer mills; dryers; pellet mills; and storage. The estimated breakeven selling price was $21.70/tonne ($1.20/MBtu). Bio-Solar was selling pellets to Western State Hospital near Tacoma, Washington, for $24/tonne f.o.b. plant (May 1978). A sensitivity analysis revealed that feedstock cost has a strong influence on the breakeven selling price.

An economic analysis supplied by Sprout-Waldron (1979) and based on a three-pellet-mill installation (224 kw each) revealed that over 50% of production costs are accounted for by feedstock and electrical energy costs (Table 9).

Whether or not it is practical and economical to pellet biomass when users have the option of directly combusting green biomass with only milling as a required preparation is a complex issue. Drying, pelleting, investment and other operating costs add about $11 per tonne of densified biomass fuel. But certain savings accrue from this additional processing because densified biomass has a higher density and lower moisture content than green biomass. Converting green biomass into pellets, cubes, briquettes, or rolls increases the number of Btus that can be transported, stored, or handled at a constant cost per unit of weight or volume. Furthermore, moisture content is a key economic factor in residue combustion systems. The lower the moisture content of the fuel, the higher the combustion efficiency of the boiler, a correlation which translates directly into fuel savings, capital investment savings because of reduced capacity requirements, and emissions control savings. It is in this area of economic analysis where more reliable information is needed about the costs and benefits of biomass densification.

The cost of other sources of energy also continually alter the picture. Hydro energy is currently in over-supply in Quebec and Northern Ontario, therefore it is a relatively low cost energy where available.

There is a social, ecological and economic value associated with densified biomass use in Canada. Remote locations with an existing pulp and paper or sawmill industry do produce waste biomass. This material would rot without any potential benefit to anyone, if not used for densified biomass fuel. The densified biomass production provides employment to people in these remote areas. The waste is used, the produced pellets are emminently suitable for energy generation in lumber drying, or pulp and paper production in close proximity to the production site.

Based on personal experience, the workers at Iroquois Falls, Ontario are very happy about their contribution to society, by being employed, reducing waste, saving the forest resource and providing alternate sources of energy.

Table 8: Approximate Energy Requirements for Pelleting by a 224 kw Pellet Mill

Feedstock	Production Rate (tonnes/hr.)	Electrical Energy Used (J/tonne)	Fraction of Product Energy Consumed (%)
Sawdust	5.5	146×10^6	2.3
Aspen wood	7.4	108×10^6	1.7
D-fir bark	4.1	195×10^6	3.1
Municipal Solid Waste	8.3	65×10^6	1.0

Source: California Pellet Mill Company and Reed and Bryant (1978)

Table 9: Estimated Production Costs for a Three-Pellet Mill Biomass Densification Facility, Capacity 18 tons per hour

Item	Cost Per Tonne (U.S. $-1979)	Percent
1. Feedstock (with 45% MC)	$ 8.51	35.9
2. Electrical (111 KW/ton)	4.89	20.6
3. Labour (four men)	1.76	7.4
4. Dryer fuel	1.18	5.0
5. Die and roll shells	0.98	4.1
6. Maintenance	0.88	3.7
7. Overhead and supervision	1.82	7.7
8. Depreciation * (11%)	3.69	15.6
TOTAL	$23.72	100.0

Source: Sprout-Waldron Div. of Koppers Co., Inc. (1979)

* Based on $1.3 million for equipment (10 yr. am.)
$2.0 million for building and installation (20 yr. am.)
Annual capacity: 111,580 tonnes

6. REVIEW OF ENFOR C-97 REPORT

Unquestionably, one of the most comprehensive research studies on the production of a moisture resistant biomass fuel is the Enfor Project C-97 "Development of a Moisture Resistant Densified Solid Fuel from Forest Biomass" by B.H. Levelton & Associates. This report has identified a number of key factors towards the production of moisture resistance.

Temperature, pressure and moisture content were studied in detail on several species. It was determined that pressing at 160°C, 20 MPa and 15-30% moisture content will produce a water stable product from pulverized wood. Bark was easier to convert to a water stable product than wood at reduced temperature, pressure and moisture level; i.e., 150°C, 15 MPa and 5-30% moisture content. Under these same reduced conditions, pulverized wood with a lignin rich binder also produced stable pellets. If one starts with a modified wood source, such as steam exploded wood, where the chemical components of the wood sample are partially depolymerized, the conditions were even milder; 150°C, 5 MPa and 0-30% moisture content.

The Levelton report also suggests a strong interaction among the three main variables. The temperature can be reduced if the pressure is increased; as moisture is reduced both temperature and pressure have to be increased to produce a water stable pellet.

This behaviour pattern is related to the glass transition temperature of wood components namely that of lignin and the amorphous portion of cellulose. Amorphous polymeric materials exhibit tackiness, brittleness, softening points and second order transitions. These non-equillibrium conditions of high polymers all arise from the same basic molecular behaviour, and are associated with increased freedom of molecular movement with an increase in temperature.

At temperatures below the softening temperature of an amorphous polymer - such as lignin - the chains are "frozen" and the bulk polymer is a brittle solid. Above the softening temperature, the chains acquire enough energy to move with respect to each other. The polymer becomes soft, deformable and sometimes tacky.

If the polymeric solid absorbs a low molecular weight dilutent, - in our case water in wood - the chains of polymer are separated by the molecules of the absorbate and require less energy to move with respect to each other. The dilutent is said to "plasticize" the polymer, and the transition or softening will occur at lower and lower temperatures, depending on the water content.

Thus, the observed behaviour that dry wood requires higher pressures and temperatures to produce a water stable pellet, or to bring the lignin into a state where it plasticizes and re-bonds the wood particles is completely anticipated. The same reasoning can be used to explain the influence of the amorphous portions of the cellulose and the hemicellulose components of wood.

In many commercial wood products and processes, the same principles apply as in the production of moisture resistant densified biomass. The production of "stay pack" or "compreg" involves the pressing of wood under high temperature to impart greater strength, density, and dimensional stability to wood. Hardboard production, i.e., masonite or arborite, type of materials, are made by pressing defiberized wood under high temperature and pressure to produce a strong, water resistant panel product. When powdered lignin is used as a binder in many applications, the lignin is brought to a temperature where it starts to flow and becomes tacky due simply to physical changes rather than due to surface chemical changes.

In papermaking, the production of thermochemical pulps, as well as the production of press boards, requires the knowledge of plastic flow and glass transition behaviour of wood, wood fibres and wood chemical components.

The above processes and products have been extensively studied in connection with glass transition temperature. Unfortunately, there is no agreement between the various publications with reference to the glass transition temperature of wood and wood components. This lack of agreement is in part due to the different methods for measuring glass transition temperatures, and in part due to the nature of the material. For example, lignin and cellulose depending on the method of preparation, have different molecular weights and functional groups and obviously have different glass transition temperatures. No one has studied some important commercial wood species at different moisture contents to show the species dependence of glass transition temperature. This fundamental information would provide an excellent background to the development of all heat formed wood products described earlier, including densified biomass.

On a practical scale, there is still one component of the process that is not sufficiently highlighted in the Levelton report. The time of pressing at a given temperature and moisture content is a critical variable. The temperatures given in the Levelton report refer to the temperature of the heating apparatus. What the temperature of the wood was, depends on the rate of heat transfer from the heating apparatus to the wood mass, and the rate of heat conduction from the surface of the wood mass to the centre parts. From the report, it appears that the wood was in contact with the heating mantle for sufficient time to be at the temperature of the mantle. In commercial processes of pelletization, briquetting or wafer forming, this is never the case. Only the surface layers of the wood are at the temperature of the die, and the rest of the biomass is at a considerably lower temperature. For this reason virtually all the commercial products are poorly bonded and non-water stable.

The method of testing of the moisture resistance of the densified biomass fuel in the Enfor C-97 report is too severe. The one hour boil test is used in the plywood, laminated wood, particle board and wafer board industry to test the stability of the products destined for outside use with an average life of 15 years. Marine plywood, exterior grade plywood are subjected to one hour boil to check the glue bond. The requirement of densified biomass is to withstand the occassional rain or snow during transport or storage for a period of 3 - 6 weeks without significant moisture gain and strength loss. It is more in line with the requirements of composite products for interior applications. These products are tested with the 24 hour water soak test at room temperature. Even this test may be too severe for densified biomass.

SECTION II

7. A SYNOPSIS OF SOME COMMERCIAL OPERATIONS BASED ON PLANT VISITS

ORF visited several densified biomass production facilities to examine first hand the production equipment, raw materials and to discuss with the production people, their operating problems and quality control programs.

7.1 BioShell Plant in Hearst, Ontario

The plant consists of a 8,360 m^2 processing building and a storage building four times the size of the processing area. The plant is employing 20 workers, usually 4 men operate the plant per shift. It is a 24 hour operation, producing 105,000 tonnes of pellets from sawmill residues supplied by three nearby sawmills. The wood is about 60% spruce, 40% jack pine with 40 - 90% MC. The bark content of sawdust is about 20% higher than in the growing trees.

The main equipment is:

- 1 hammer hog to process the wood waste
- wood dust burner to generate heat for wood drying
- rotary 3 phase drum suspension dryer to reduce chip moisture from 50% to about 15-20%
- 2 hammer mills for particle size reduction with 150 kw motors each
- 4 pellet mills with 224 kw motors, each, 2 California pellet mills, 2 Sprout-Waldron mills
- 2 shaker screens to remove fines
- 2 coolers to cool chips and pellets
- 1 boiler
- Several screw feeders and conveyor belts

The operation requires 600 volts of electricity with 3000 Kw load for operation, 30 L of water for chip and pellet conditioning, 140 Kg of wood-dust or 7 m^3 of natural gas if wood is not available for drying.

The pellets are: 6 mm in diameter, 19 mm in length, density of 1.06 g/cm^3, with a bulk density of 600 Kg/m^3. The heating value is 18.6 MJ/Kg, ash content less than 3%, moisture content 6-8%. Die-life is 3000 tonnes/die. The equipment maintenance is their main problem.

The plant is very modern and well instrumented. Pellet density and quality is determined by measuring the temperature increase due to friction and compression in the die area. The friction is changed by putting more, or less, steam in the screw feeder area.

The chips are fed into the pelletizer area at 94^{0}C, and the feed develops a 18^{0}C increase in temperature to 112^{0}C. The amount of steam determines the friction heat generated, more steam means less friction; dryer wood results in higher friction heat generation. The computer controls the steam injection on the basis of a set point.

The finished pellets are mainly used by Abitibi-Price paper, and are shipped in covered trucks. The plant operates at full capacity from September to May. In the summer, due to lack of storage space, the operation slows down.

7.2 N.S. Bauman Ltd., Wallenstein, Ontario

The plant has one 224 kw model 26-300 Sprout-Waldron pelletizer. The unit is run for about 2 - 3 days a week on a 10 hour shift basis to make biomass fuel from hardwood (mainly maple) sawmill waste. The remaining days of the week, it is used to pelletize agricultural crops and stale bread for livestock feed. In the past four years, production of biomass has quadrupled.

The suspension dryer unit is outside of the building, very likely affecting the heat efficiency, especially during the winter months. Production rates are 2.5 - 3.0 tonnes/hour or about half that of the BioShell plant.

The die temperature is considerably lower than at BioShell (71°C). The pulverised chips are screened for removal of fines before being fed to the pelletizer. This is used to heat the dryer. At BioShell, the finished pellets are screened to remove fines and this is being used to heat the dryer. The unit has no computer control to measure and control the pelletization process.

The pellets are sold to greenhouses in bulk or to local households in 13.5 kg bags to use in wood burning furnaces.

Pellets made by N.S. Bauman Ltd. are the same in dimension and physical properties, to that of BioShell. The pellets are somewhat denser and have higher heating value.

7.3 Dofasco Limited, Hamilton, Ontario

Two model F.H. 50/150 Fred Housemann briquettors are producing for about 12 hours/day, 5 cm diameter 1.2 - 2.5 cm deep wafers.

Dried (less than 20% moisture) hardwood or softwood chips are used. Dofasco has no dryer, but has a hammermill for size reduction. The feed is not screened.

Wafer pressing is controlled by the die temperature. Cold water and steam lines are attached to the die unit. Die temperature at running conditions is 110°C. During start up, steam is used to heat up the die. In continous operation, cold water is needed to cool the die. The heat is generated by friction and compression.

The wafers are weak in comparison to BioShell and N.S. Bauman products. The product is used to quiet-down the sputtering of the molten steel from the blast furnace. It also reduces slag formation.

7.4 Fire Logs

The writer also visited 2 plants producing fire logs. One from wood chips alone, while the other was from a mixture of wood chips, metallic additives for improved flame colour, and waxes and oils.

These operations are geared to produce consumer products for fire places. Considering the low heating efficiency of fire places and the relatively high cost of fire place logs, we believe these products have only an esthetic value at the moment. For this reason, we feel that the operations are not significant for energy generation in Canada.

In short, the five plant visits were extremely valuable to bring into our research efforts a better understanding of the need of the industry, the practical unit operations, the raw materials used, and the equipment involved in biomass densification.

SECTION III

8. THE EFFECT OF PARTICLE SIZE ON DENSIFICATION

8.1 Background

Virtually all heat-bonded wood and paper products, such as masonite, press-board, compreg and staypack, as well as the pelletized biomass are primarily held together by lignin bonding. This lignin bonding comes about by the lignin component of the wood being softened during the heating step and forming the bonds after the product is pressed and then cooled down.

In pelletized biomass, the contact area between the various particles is obviously influenced by the shape, the size distribution and the surface roughness of these particles.

In the Levelton and Associates report (Enfor C-97), many critical variables were studied with respect to the formation of moisture resistant densified biomass. Moisture content, temperature and pressure interactions on five major commercial species of Canada (hemlock, maple, red alder, spruce and poplar) were studied. For each species, wood and bark were evaluated separately.

We observed from the Levelton and Associates report that for the same species, the pellets containing bark were formed into a moisture resistant pellet at a lower critical combination of variables (MC %, temperature and pressure) than for the pellets containing wood. The particle size distribution of bark feed for pelletization was significantly finer than the size distribution of wood feed for pelletization. Our interpretation of these results was that lower average size, finer particles form better pellets, possibly due to better contact at any given pressure and temperature with each other and the die. In addition, the finer particles may be in the "glass transition" state throughout the entire cross-section of the particles while the larger particles are only affected in the surface regions.

This reasoning led us to study particle size effects in detail.

8.2 Experimental

We have used debarked mature Jack pine (*Pinus banksiana Lamb.*) throughout our studies.

The green wood was chipped in a commercial chipper normally producing chips for pulping operations. The green chips were brought to about 15 - 25 % moisture content by air drying.

A portion of the air-dried chips was passed through a laboratory hammermill. Since the comminuted wood contained a sizable amount of large particles (greater than 0.5 cm), the wood was further broken down in size by passing it through a 30 cm diameter "Sprout-Waldron" double disk refiner. In this dry pass, the refiner housing was air cooled with 275 kPa of air. The clearance of the refiner plates was set at 1.25 mm.

The coarse fraction of the refined wood was separated by passing the material through a 0.5 cm screen. The size distribution of the wood passing through the 0.5 cm screen was determined by passing a portion of it through the following series of Tyler screens.

SCREEN NUMBER	APERTURE SIZE (mm)
8	2.36
10	2.00
12	1.68
20	0.84
40	0.42
80	0.18

The investigation of the effects of maximum press temperature, wood furnish size, and wood moisture content on moisture resistance was accomplished by the use of a "Pneumet" pneumatic mounting press made by Buehler Limited. The mold assembly used had a diameter of 25.4 mm (1 inch). Heat was provided by a thermostatically controlled electric heating jacket. Maximum mold temperature was controlled by means of a "Powerstat". Temperatures were measured with a spring-type thermometer, whose attached metal rod was placed down the centre of the punch.

Typically, 4.0 g of air-dry wood was placed into the mold. Pressure was applied at 27.6 MPa (4,000 p.s.i.). After heating the mold to its maximum temperature and removal of the heater, the pressure was released in order to flash off steam generated by the water in the wood pellet. The same pressure was then re-applied and the mold was cooled to about 80°C by means of a water-cooled jacket. The DBF pellets thus produced, varied in thickness from about 5 to 6 mm. The entire pressing/cooling cycle took about 20 minutes. Levelton and Associates used identical equipment and methods for their investigations.

Five (5) DBF pellets were pressed at each of the following conditions:

1. + 8 fraction, 19% MC: 130°C, 140°C, 150°C, 160°C, 170°C
2. +10 fraction, 19% MC: 130°C, 140°C, 150°C, 160°C, 170°C
3. +12 fraction, 19% MC: 130°C, 140°C, 150°C, 160°C, 170°C
4. +20 fraction, 19% MC: 130°C, 140°C, 150°C, 160°C, 170°C
5 -20 fraction, 19% MC: 130°C, 140°C, 150°C, 160°C, 170°C
6. Combined refined wood, 19% MC: 130°C, 140°C, 150°C, 160°C, 170°C
7. Combined refined wood, 30% MC: 130°C, 140°C, 150°C, 160°C, 170°C

The combined refined wood had been passed through a 0.5 cm screen in order to remove the coarse particles.

The pellets were then conditioned at 23°C and 50% relative humidity until they reached "equilibrium weight", i.e., until their weight change was less than 0.1% per 24 hours. One pellet per experimental condition was then oven-dried at 105°C and its oven-dry weight and conditioned moisture content were determined. This information was used to calculate the oven-dry weights of the remaining four pellets in each group.

Thicknesses of the conditioned pellets were measured by means of a dial micrometer and their volumes were calculated. Pellet densities were calculated on an oven-dry weight basis by dividing the oven-dry weights by their respective conditioned volumes.

The water stability of the pellets was assessed by means of a 24 hour immersion test. In this test, the pellets were placed in water at 23°C for 24 hours. The thicknesses and weights of the pellets were checked before and after the test and percent changes were calculated. A pellet was said to be water stable when the change in thickness was no more than 10%. Two pellets per sample were evaluated.

In this respect, our procedure is very different to that adopted by Levelton and Associates. In their Enfor C-97 report, a one (1) hour boil test was used. ORF believes that this is too severe for testing water stability for densified biomass fuel. Some of the pellets were photographed before and after the 24 hour soak test.

Pellet crush strength determinations were performed on an Instron "Model 4201" universal testing machine. Pellets were loaded to failure across their diameter at a uniform crosshead speed of 5 mm/minute. The load required to initiate crushing of the pellet was recorded. The crush strength in MPa was calculated by dividing the maximum load by the projected area of the pellet (length x diameter). For each sample, two pellets were crushed.

8.3 Results

The size distribution of the comminuted Jack pine wood is shown in Figure 3. The mean particle size of this material was approximately 2.0 mm.

The differences in the various size distributions in the five fractions studied are visually depicted in a photograph (Figure 4).

The appearance of the pressed pellets changed markedly with increasing press temperature. Typically, the pellets produced from the coarse fractions at the lower temperatures were light in colour and dull in appearance. With increasing temperatures, the pellets took on a dark brown, shiny appearance. This change in appearance would commence at a lower temperature as the particle size was reduced. It was also noted that the pellets produced from a 19% MC furnish tended to have a non-uniform appearance in two respects. Firstly, the shiny, dark pellets produced at the higher temperatures frequently had a lighter, non-shiny region around their peripheries. Secondly, the surfaces in contact with the bottom of the mold were usually lighter in colour than the surfaces in contact with the top of the mold. The pellets produced from a 30% MC furnish also exhibited the latter non-uniformity, however, the former one was lacking. Photographs of some pellets pressed from different fractions at different temperatures are shown in Figure 5.

Average pellet densities and average pellet crush strengths for the pellets produced from the variously sized wood fractions at different maximum press temperatures are reported in Table 10. In Table 11, the average pellet crush strength for the various wood fraction sizes is reported. Here, the average crush strength represents the average of the values obtained at the five temperatures.

The results of the 24-hour water immersion tests are given in Table 12.

Pellet densities, pellet crush strengths, and thickness swellings (%) are depicted in Figures 6, 7, and 8, respectively, for the seven different particle size combinations as a function of press temperature.

8.4 Discussion of Results

Some of our experimental results which were already presented in table form and discussed in the ORF Report No. 48-10383, 1985 November 22nd, are presented through photographs and graphical form in this report.

Figure 4 depicts the particle sizes of the five fractions used in this study. The average particle size of the combined fractions was about 2 mm. This value is similar to the average particle size of the feed for the two commercial pelletization units at Iroquois Falls and Wallenstein, Ontario, as well as the feed used in the Levelton and Associates report. Thus, the findings of this report should be applicable to commercial units and compared to previous Canadian research results. The size distribution within the subsamples was fairly uniform. Note that there is no colour difference between the samples prior to pressing.

Photographs in Figure 5 are intended to demonstrate the influence of die temperature and particle size on the colour of the samples. The darker colour resulting from higher die temperature is fully anticipated. The darker colour of pressed pellets made from decreasing particle size feed is somewhat more difficult to explain.

One possibility is that the smaller particles conduct the heat from the die into the pellet due to larger relative contact areas with the die better than the large particles.

The concentration of lignin within the wood structure is highly variable. The middle lamella layer of the fibre cell wall contains a high concentration (85%) of lignin, while the secondary wall layer of the cell wall is mainly (80%) cellulose and contains relatively little lignin (20%). During heating and pressing, it is possible that the lignin heated to the thermoplastic glass transition state flows to the surfaces of the particles, while the cellulose remains stationary in the center of the particles. Since the average distance the lignin has to flow is less in the case of the smaller particles than in the case of the larger particles, darker colour of the small particles appears plausable via this mechanism. Simplistically, the softened lignin is squeezed out to the surfaces from the rigid cellulose network.

The effect of press temperature on pellet density from the various fractions and combined feed, depicted in Figure 6, is in line with our anticipations.

At virtually all temperatures tested, the largest fraction produced the lowest density pellets. One point at 160°C press temperature is an exception. The smallest fraction tests (-20) produced the densest pellets at 130°C, 140°C and 150°C. At the two higher temperatures tested, 160°C and 170°C, the results were not in line with expectations. At 160°C the densest pellets were made from the combined fraction at 19% MC, while at 170°C the densest pellet was made from the +10 fraction. The variability of these results are ascribed to experimental error. The general trend from Figure 6 is increasing pellet density with decreasing feed particle size.

The combined fraction at the same moisture as the individual fractions produced definitely higher density pellets than the coarse fraction (+8) and at the high temperatures (160°C and 170°C), possibly higher density than the fine fractions. The smaller particles in the combined furnish fill in the holes in the structure.

The combined fraction at 30% MC produced the lowest density pellets. The steam generated during the pressing cycle obviously interferes with densification at this high moisture level and therefore moisture levels of 30% should be avoided.

The reason for taking such a close look at density of the pellets at various forming conditions stems from the observation presented in the Enfor C-97 report "...that at about 1.3 g/cm^3 density moisture stability is achieved regardless of the method of achieving this density level".

Data presented on pellet crush strengths in Figure 7 presents a clearer indication that pellet strength is increased as particle size is reduced.

The +8 particle size curve is the lowest strength, while the -20 is the highest strength on this graph. Other sizes follow in order of +10, +12, and +20 fractions. The combined fraction at 19% MC gave average strength roughly equal to the smallest particle size samples. Again, the combined fraction pressed at 30% MC was weak, due to the steam formed during pressing. This steam likely interferred with the development of high bonding strength in the pellets.

The most important property of the densified biomass fuel is moisture stability. We defined moisture stability as <10% change in dimensions. Generally speaking (Figure 8) water stability increased as press temperatures increased and decreased with increasing particle size. The combined fraction with 30% MC wood produced more stable pellets than the same fraction with 19% MC wood. This occurred in spite of the higher density and greater pellet strength of the latter pellets. High MC is thus beneficial if not from the standpoint of pellet strength or density, but from the standpoint of water stability.

Figure 9 depicts the appearance of the pellets after the 24 hour water immersion test. The pellets from the -20 fraction pressed at 150°C showed a minor delamination through the middle of the pellet and some loosening at the edges (Figure 9A). The pellets from the +12 fraction were almost completely separated through the middle portion, and contained several loose particles around the edges (Figure 9B). Pellets formed from the combined fractions, pressed at 130°C had virtually no strength after soaking (Figure 9C).

Recapping the results, both pellet density and pellet crush strength increase with increasing press temperatures (Table 10). At the same time, pellet stability increases while water pick-up decreases with increasing press temperatures (Table 12). The same trend is observed with decreasing wood fraction sizes of the feeds.

In the Enfor C-97 report, it was found that press temperatures above 155°C, at 27.6 MPa, produced pellets which exhibited water stability. On the other hand, our pellets, produced even at 160°C and 170°C, were not generally water stable. This is in spite of the differences in testing conditions (1 hour boil - Enfor C-97, vs 24 hour soak at room temperature - ORF). The Enfor C-97 study test being much more severe than the ORF method.

It is crucial that moisture is retained in the wood while it is held under pressure and elevated temperatures. The escape of the original water from the wood during pressing would prevent the attainment of desired process conditions for water stability. This may have been the reason for the observed differences.

SECTION IV

9. ADHESIVES

Background

In late April and early May, 1985, Mr. A. Hansmann and Dr. G.A. Matolcsy visited technical representatives from eight adhesive manufacturing companies to obtain recommendations of a glue or glue system from their line of products which would produce

- an economical,
- water resistant,
- non-dusting
- and strong

biomass fuel. We asked for brochures on these product lines and recommended addition levels, methods of addition and May/1985 costs.

We contacted specific companies with product lines in the area of natural adhesives. The meetings lasted 1 - 2 hours with each group.

Table 13 summarizes the information gathered. Unfortunately, none of the companies had experience in this particular field and therefore could not recommend specific formulations. They all "promised" to look into the matter and do some experimental work but there has been no response to date.

We also contacted the President of Bioshell Canada Ltd. to ask what would be the maximum amount one could spend on a glue for Energex pellets and still be competitive. His answer was that the price of wood chips determines economics to a large extent. So if one has a cheap source of chips close to the converting plant, then one can afford to spend more on the glue than if the reverse is true. Some of the information disclosed by him is confidential.

9.1 Lignin Based Adhesive Systems

Dr. G. Matolcsy also visited Forintec Corp. and talked to Mr. Louis Calve, a specialist in lignin based adhesive systems. Lignin based adhesives were high on our original proposed list of priorities because of the low price [9 - 11¢/kg on liquid resins (50% solids), 20¢/kg on powders]. Three publications were given to us by Mr. Calve and these were reviewed.

In the final analysis there is little hope that lignin based adhesives will do any better than heat treatment alone. Lignin is in the class of thermosetting resins. The curing temperature is very high, equal or higher than the glass transition temperature of wood.

In panel products, platten temperatures of 210°C - 235°C for five minutes on a 6 mm product are required. Post curing of several hours in an oven at 200+°C is also required. These temperatures with pressure (27 MPa) would produce on a moist wood (15 - 30% MC) a completely moisture resistant pellet without any adhesive. Therefore the use of lignin is just an added cost.

From the list of adhesives that were reviewed by us with the glue companies, the most promising ones are:

9.2 Crude Tall Oil Rosin - $0.66/Kg

This is also a waste product of many Kraft mills that is not being recovered. Therefore to find a use for it is desirable. The material is not so much an adhesive as a sizing agent to improve the water repellency of densified biomass. In a later section, we will present some results on the performance of this material.

9.3 Crude Tall Oil Pitch - $.31/Kg

Same comments as 9.2.

9.4 Coal Tar Distillate Fractions (Pitch-liquid, pitch-solid, emulsion and sludge)

Based on a report "Development and Demonstration of a Lignite Pelletizing Process" (by the Pittsburgh Mining Technology Center, Pittsburgh, Pennsylvania), the above materials show a promise. The above fractions are all hydrophobic and combustible with a higher BTU value than wood. They significantly improved lignite and peat pellet strength and moisture resistance. We would also expect good performance with wood.

The problem we faced was to work out a method of addition. At room temperature the products are very viscous or solid. Emulsions commercially available are made with 20% inorganic components as a rule. The inorganic clay is used for nucleation of the particles. Originally, we planned to use an organic nucleating agent, such as walnut shell flour to produce an emulsion from coal tar distillate fractions, but we have been unable to accomplish this within the time frame of our project.

9.5 Starch - Dextrine Based Adhesives

These materials have shown poor performance on lignite and peat. We have decided to ignore these products in favour of others based on published information of their performance on lignite and coal pellets.

9.6 Waste Wax and Waste Waxed Paper, Polyethylene and Polypropylene Wastes

These materials all show very good potential. It is a matter of availability and mode of addition to the process stream. Possibly the greatest disadvantage of waste polyolefin materials, especially polyethylene and propylene is that films, ready formed particles, or trimmings from sheets or round objects from other wastes, cannot be readily converted into powder form.

Any mechanical conversion generates heat. This heat would melt these polymers. The only known techniques to comminute polyolefins is by cryogenic techniques. The cost of cooling the product to the brittle state, however, is prohibitive.

10. EXPERIMENTAL

As in previous trials, we used comminuted Jack pine (Pinus banksiana) as the wood furnish. The preparation of this wood, as well as its size distribution, have been described in the previous section dealing with particle size.

To determine the effectiveness of binders for producing a water-stable DBF, the following binders were evaluated:

1. Polyethylene powder (BDH Product No. 1504f6 - for chromatographic analysis),
2. Crude tall oil rosin (Hercules Canada Limited),
3. Core pitch (100% coal tar pitch, flasked solid obtained from Domtar Inc.),
4. Waste polyethylene film,
5. Waxed corrugated fibreboard,
6. Pine tar binder (Crowley Tar Products Co.).
7. Petroleum vacuum residue - light Arabian (Petro-Canada Limited)
8. Tall oil pitch (Hercules Canada Limited).

The crude tall oil rosin and the core pitch were ground to a fine powder by mortar and pestle. The waste polyethylene film and the waxed corrugated fibreboard were comminuted by means of a laboratory Wiley mill. No melting occured during processing.

The waste polyethylene film was obtained in shredded form through Ontario Research's Waste Materials Exchange. Some paper fragments were mixed in with the polyethylene film. By dissolving the cellulosic fibres with CED (cupriethylenediamine), we determined the polyethylene content to be about 84%.

The waxed corrugated fibreboard "binder" was obtained by grinding up a waxed corrugated fibreboard carton. The wax content of the comminuted material was determined by a chlorothene extraction. The material contained about 20% wax (oven-dry basis).

Comminuted Jack pine wood at 30% moisture content was mixed with 2% and 5% polyethylene powder, as calculated on the weight of the moist wood. Each pellet was pressed from 4.0 g of wood/binder mixture in a "Pneumet" pneumatic mounting press. The pressing scheme has been described in the previous section dealing with particle size. For each binder addition level, five pellets were pressed at 130°C, 140°C, 150°C, 160°C and 170°C.

In order to determine the effect of the moisture content upon the pellets made with polyethylene powder binder, we pressed additional pellets from wood adjusted to 19% MC. Since the binder addition levels (2% and 5%) were based on a moist wood basis, i.e. wood plus moisture, we had to add a corresponding amount of binder based on the oven-dry (OD) weight in order to achieve comparative binder addition levels. For the 2% addition level, the corresponding OD-based percentage was 2.7%. Once again, pellets were pressed at 130°C, 140°C, 150°C, 160°C and 170°C.

Initial test results showed that the pellets made from wood at 30% MC tended to have a greater water stability than pellets made from wood at 19% MC. However, the 30% MC pellets also recorded a lower crush strength. Since our primary objective is to develop water stable pellets, we decided to fabricate the remaining pellets from wood adjusted to 30% MC.

Ground crude tall oil rosin and ground core pitch were added to comminuted Jack pine wood (30% MC) at levels of 2% and 5%. For each binder addition level, five pellets were pressed at 130°C, 140°C, 150°C, 160°C and 170°C.

Since the waste polyethylene film contained about 16% paper, it was admixed with the Jack pine wood at a somewhat higher addition level, namely 3.5%. By the same token, waxed corrugated (approx. 20% wax) was added at a level of 17%. Once again, pellets were pressed at 130°C, 140°C, 150°C, 160°C and 170°C.

The Pine tar binder, the petroleum vacuum residue, and the tall oil pitch (Adhesives 6, 7, and 8 in our list) were all highly viscous liquids at room temperature. Consequently, it was necessary to dilute these viscous substances with xylene. The dilution of Pine tar binder was 2:1 (Pine tar : xylene) while the petroleum vacuum residue and tall oil pitch were both diluted 1.33:1 (binder : xylene). The resulting liquids could then be sprayed onto the wood furnish by a misting bottle. Vacuum residue and Pine tar were added onto the wood furnish (30% MC) at a rate of 2% and 5% solids each, based on moist wood weight. Tall oil pitch was only added at 2% solids, based on moist wood weight. The solvent was allowed to evaporate prior to pressing at maximum press temperatures of 130°C, 140°C, 150°C, and 170°C and 27,600 kPa pressure.

All pellets made were conditioned at 23°C and 50% relative humidity until they reached "practical equilibrium weight", i.e. until their weight change was less than 0.1% per 24 hours. One pellet per sample was then oven-dried at 105°C and its oven-dry weight and conditioned moisture content were determined. This information was used to calculate the oven-dry weights of the remaining four pellets in each group. Pellet density, pellet water stability and pellet crush strength determinations were carried out according to methods described in the previous section of particle size.

11. RESULTS

Average pellet densities and average pellet crush strengths for the pellets produced with the various binders at different maximum press temperatures are reported in Table 14. For comparative purposes, the results obtained with 100% Jack pine are also given (taken from Table 10 of the previous section). The results of the 24-hour water immersion test are outlined in Table 15.

In Table 16, the average crush strength of the pellets produced with the various binders is reported. In this case, the average crush strength represents the average of the values obtained at the five temperatures.

Pellets formed from wood containing rosin and core pitch binders frequently stuck to the surfaces of the mold even though a silicon-based release agent had been previously applied. This sticking was most severe with pellets produced at the higher temperatures from furnishes containing 5% binder. On the other hand, pellets made with polyethylene and waxed corrugated separated quite easily from the mold.

Figures 10 and 11 depict the change in pellet density as a function of increasing press mold temperature for pellets made with polyethylene, rosin and core pitch at the 2% and 5% addition levels, respectively.

Figures 12 and 13 show the change in pellet crush strength as a function of press mold temperature made with the same additives as above at the same addition levels (2 and 5%).

Table 17 presents the influence of changing the moisture level from 19 to 30% when using an additive.

11.1 The Physical Appearance of the Pellets After Pressing

Pellets made with 2% and 5% polyethylene powder had similar appearances. Those pressed at 130°C and 140°C temperature showed no discoloration, but had a natural pine colour. At 150°C press temperature, a slight darkening occurred; the pellets became progressively browner in colour at 160°C and 170°C press temperatures.

Pellets made with 2% and 5% rosin were identical in colour to the previously described pellets. A tacky coarse structure could be felt on the surfaces.

Pellets made with coal tar pitch were dark brown to black in colour, especially on the circumference of the cylindrical pellets. Those made were 5% coal tar pitch were darker than those made with 2%. The pitch appeared to be evenly spread on the wood particle surfaces.

Pellets made with 2.26, 3.5 and 5.1% waste polyethylene film were identical in colour and feel, to the pellets made with polyethylene powder and rosin size. The same description fits the samples made with 20% waxed corrugated paper.

The samples made with petroleum vacuum residue were similar in colour to those made with coal tar pitch.

The samples made with pine tar had a somewhat darker colour than those made with polyethylene or rosin size.

Some photographs presented in Figure 14 illustrate the points discussed above.

11.2 The Physical Appearance of the Pellets After 24-hours Immersion Tests

Pellets made with 2% polyethylene powder at 130°C press temperature easily fell apart after the water soak tests. None of the other pellets made with polyethylene powder showed any loose particles or delamination. These pellets were smooth, shiny and strong after the 24-hour soak. For practical purposes, these pellets were all water stable, but by our definition of <10% dimensional change, only those pellets pressed at 160°C and 170°C passed the test.

Pellets made with 2% and 5% rosin were structurally less stable than the pellets made with polyethylene powder. Pellets made with 5% rosin were better than those made with 2% but even the pellets pressed at 150°C, 160°C or 170°C showed the occasional crack through the thickness of the pellet.

The integrity of pellets made with 2% & 5% core pitch was very low after soaking for those pressed at the low temperatures [130°C and 140°C]; while those made at 150°C, 160°C and 170°C were strong, retaining their structural integrity.

The structural integrity of pellets made with various percentages of waste polyethylene were as good, or better, than those made with polyethylene powder.

The samples made at 130°C and 140°C with 25% waxed corrugated paper (5% wax addition) fell apart after soaking. The edges of some of the remaining pellet samples were weak. However, these samples were not the worst.

The samples made with petroleum vacuum residue were even weaker, especially at the 5% add on level. Most samples fell apart after the soak test, with the exception of those made at 160°C and 170°C press temperatures.

The pine tar samples were the worst in terms of integrity after the 24 hour soak. At the low temperatures, they completely disintegrated, and those made at high press temperatures delaminated, or their edges feathered.

Some photographs presented in Figure 15 illustrate the effect of water on the various pellets.

12. DISCUSSION OF RESULTS

From the large number of additives tested (see Table 14), the pellet densities at any press temperature were not greater with polyethylene powder, polyethylene film, waxed corrugated paper, rosin size, core pitch material and tall oil pitch than with Jack pine alone. The adhesives did not appear to promote binding with these materials. Furthermore, an increased addition level of the adhesive produced pellets virtually of the same density as the lower level of addition.

The petroleum vacuum residue, and the Pine tar binder on the other hand produced pellets of about 3 - 10% higher density than Jack pine alone, or the previously listed additives added to Jack pine. By increasing additive levels from 2% to 5% for both of these binders (vacuum residue and pine tar) the density increased further.

With respect to average pellet strength (Table 16), polyethylene powder, tall oil pitch and waxed corrugated fibres each reduced crush strength compared to that observed on 100% Jack pine. Rosin size, core pitch, waste polyethylene film and petroleum vacuum residue increased pellet strength compared to that of the 100% Jack pine pellets. The results on pine tar blend were ambiguous, at the low addition level (2%), the strength was equal to that of the 100% Jack pine pellets but at the 5% addition level crush strength was reduced by nearly 20%.

The greatest benefit derived from the use of additives was in the improved dimensional stability of pellets in the water immersion tests (Table 15). Examining the water weight pick up or the thickness swelling of the untreated Jack pine pellets (Table 12), one can readily see that regardless of the composition, the pellets pressed at 130°C, 140°C or even in some cases, at 150°C showed 100% weight gain or dimensional change. At higher temperatures, improved stability was observed (at 160°C or 170°C swelling was at 15 - 50% range). With most of the additives, as press temperature increased (from 130°C to 170°C), the water stability was doubled (or more) over that of the untreated Jack pine pellets.

Many of the pellets made with additives produced water stable pellets at the 160°C and 170°C press temperatures (Table 15).

Polyethylene powder at 5% addition and at 160°C and 170°C press temperatures provided water stability to the pellets allowing only 4.8% and 4.5% dimensional movement of the pellets. Excellent results were obtained with the polyethylene film at these same press temperatures at the 3.5 and 5.1% addition levels (4.9 - 9.3% change in dimension).

Other materials that produced respectable water stability were tall oil pitch and rosin size, but as previously mentioned, these materials tended to stick to the mold.

The waxed corrugated paper and the petroleum vacuum residue were disappointing in water stability with respect to the other materials we have tested. The core pitch was also relatively ineffective in producing water stability.

Taking into consideration the method of application to the biomass, cost and performance, of all additives, the polyethylene waste appears to be the number one choice.

SECTION V

13. PRODUCTION OF PILOT SCALE PELLETS

The objective of this phase of the work was to produce pilot scale quantities of pelletized biomass for evaluation of physical characteristics and heating performance in a domestic furnace.

13.1 Experimental

Green, mature jack pine bolts were debarked and chipped at the Abitibi Research Centre in Sheridan Park, Mississauga. The chips had a size distribution normally used in pulping operations, about 2 cm x 1 cm x 0.3 cm. We produced approximately six 45 gallon drums of this material. The moisture content was 44%. These chips were further comminuted using a laboratory scale 60 cm diameter "J. M. Fiberiser" made by Fournier Steel Works. Four hammers were used at 1800 RPM speed in the fiberiser. These chips were shipped to Shell Co. Ltd. pilot facility in Oakville, Ontario.

Shell judged this material to be too coarse and further hammermilled this material to obtain a particle size distribution shown in Figure 16.

The average particle size of this feed was about 0.8 mm, considerably smaller than that used in our laboratory scale pressings. The laboratory pellets were made from a feed of 2.0 mm average size.

Shell dried the comminuted jackpine to various moisture contents in the range of 5-12% MC.

These samples were pelletised on a 2 HP pilot scale California Pellet Mill using dies of different thicknesses. At least 1 kg of pellets was made in each trial. Visual and handling assessment were used to select the optimum pelletising parameters. The optimum MC % was 9.4%. This was used to produce 70 kg of pellets.

Initially, we intended to produce the extruded pellets with the addition of the waste polyethylene film binder. Unfortunately, we were unable to obtain large quantities of this material.

We used a low density, high melt index injection molding grade polyethylene (Dow Chemical's "resin 955"). This resin has a melt index of 35 g/10 mins and a density of .923 g/cm^3. The beads of resin were ground to pass a screen of 2 mm opening on the Willey Mill. The polyethylene was also shipped to Shell laboratories.

Shell has thoroughly mixed in 2% and 5% portions of polyethylene, respectively, based on oven dry fibre weight with jack pine feed, in a fibre drum tumble mixer.

The MC of the feed and operating parameters on the pellet mill were the same for the polyethylene additive blends as with the pure jack pine chips. About 75 kg of pellets from each of the blends (2% and 5% polyethylene) were made.

Drums of the three different types of pellets were returned to Ontario Research for burning tests and evaluation of physical characteristics

13.2 Physical Properties

Oven dry density (O.D. weight/O.D. volume) determinations were carried out on the three extruded pellet sample lots. About 100 g of each sample were oven dried at 105°C, and the oven dry weights were recorded. The pellets were dipped in molten wax. The waxed pellets were placed into a wire basket. The wire basket and pellets were submerged in water at 23°C. Gross weights were recorded in air and in water. The volume of pellets was obtained by subtracting the net weight in water from the net weight in air. Corrections were made for the weight and the volume of wax coating.

Pellet density was calculated from the pellet weight and volume (Table 19).

Shake tests were conducted, in duplicate, on the three extruded pellet samples. The test procedure consisted of screening the material to obtain a 400 g specimen of plus 0.5 cm material. This material was then placed into an 8 mesh Tyler sieve and shaken for 15 minutes on a Tyler sieve shaker. The material was then removed and re-screened on the 0.5 cm screen to determine weight loss.

Heating or calorific value determinations were carried out on the following pressed and extruded pellet samples:

(1) Laboratory-pressed pellets - 100% jack pine (Pj), Pj + 5% core pitch, Pj + 5% rosin, Pj + 5% pine tar, Pj + 3.5% waste polyethylene, and Pj + 5% waste polyethylene.

(2) Extruded pellets - 100% Pj, Pj + 2% polyethylene, Pj + 5% polyethylene, and commercial Energex pellets.

The Btu value of these samples was determined by using the Paar Adiabatic Bomb Calorimeter following ASTM Method D 2015-66. The results were not corrected for ash and sulphur content, but adjusted for variability in moisture.

13.3 Results

The particle size distribution of feed for the commercial pellets is given in Figure 16. The physical properties of the samples of extruded pellets is given in Table 19. The calorific analysis of the laboratory and pilot scale pellets is given in Table 18.

13.4 Discussion of Results

The particle size (Figure 16) of the feed for the commercial unit was lower than for the laboratory experiments (average 0.8 vs 2.0 mm). The feed produced by Shell was also lower in average size than the commercial feed used at Iroquis Falls and Wallenstein. This difference, in our opinion, helped in the formation of better pellets.

The density values of these experimental pellets were higher than those generally obtained in commercial operations (Table 19 vs Tables 4-7). The values of jack pine, jack pine with 2% polyethylene and jack pine with 5% polyethylene were 1.333, 1.300 and 1.271 g/cm^3, respectively. The polyethylene acted as a lubricant during the compression cycle and this caused the 5% reduction in density.

Not all the polyethylene was completely melted by the extrusion process. The surface layers had a good coating but, in the centre portions of the pellets (2/3 of the diameter), the polyethylene was only partially melted. This caused some weakness and insufficient water stability.

The moisture contents of the three samples (Table 19; 6.6% - 8.7%) were similar to those generally obtained on the commercial Energex pellets.

Polyethylene (PE) increased the heating value by approximately 5% for the pellets containing 5% PE and by approximately 2.5% for the pellets containing 2% PE compared to the pure jack pine. The pellets produced by Shell Co. Ltd were 10% higher in heating value than Energex pellets. Generally speaking, all the additives (core pitch, rosin, pine tar, waste polyethylene) improved the heating value compared to jack pine alone (Table 18).

The results of our shake tests (Table 19) and visual evaluation showed that pellets made with polyethylene had better strength and structural integrity than either Energex pellets or those made with pure jack pine.

The water soak test gave disappointing results. We selected some of the best pellets for the water soak tests. In spite of this selection, the pellets disintegrated after 2 minutes of soaking. In our opinion, the water soak test is too severe to check moisture resistance.

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TABLES AND FIGURES

TABLE 10: AVERAGE PELLET DENSITY AND AVERAGE PELLET CRUSH STRENGTH vs. WOOD FRACTION SIZE AND MAXIMUM TEMPERATURE

PELLET IDENTIFICATION	PRESS TEMP. °C	AVERAGE DENSITY kg/m^3	AVERAGE CRUSH STRENGTH, MPa
+ 8 fraction, 19% MC	130	1151 ± 11	3.37
	140	1163 ± 11	3.68
	150	1175 ± 7	3.66
	160	1199 ± 11	4.39
	170	1197 ± 13	4.99
+10 fraction, 19% MC	130	1166 ± 30	5.56
	140	1188 ± 23	5.29
	150	1185 ± 34	4.69
	160	1194 ± 36	6.61
	170	1266 ± 12	7.23
+12 fraction, 19% MC	130	1152 ± 43	3.53
	140	1193 ± 15	5.33
	150	1195 ± 45	5.35
	160	1233 ± 23	6.64
	170	1228 ± 12	7.67
+20 fraction, 19% MC	130	1158 ± 11	5.49
	140	1174 ± 12	6.04
	150	1200 ± 8	6.65
	160	1224 ± 31	10.12
	170	1258 ± 34	9.15
-20 fraction, 19% MC	130	1187 ± 5	9.88
	140	1207 ± 22	10.76
	150	1211 ± 11	9.51
	160	1212 ± 16	8.00
	170	1227 ± 12	9.57
Combined, 19% MC	130	1166 ± 31	6.44
	140	1174 ± 24	6.81
	150	1197 ± 36	7.36
	160	1238 ± 9	7.68
	170	1234 ± 17	9.39
Combined, 30% MC	130	1106 ± 14	2.57
	140	1137 ± 10	3.37
	150	1146 ± 9	4.51
	160	1177 ± 15	5.47
	170	1159 ± 17	5.56

TABLE 11: AVERAGE PELLET CRUSH STRENGTH vs. WOOD FRACTION SIZE

PELLET IDENTIFICATION	AVERAGE CRUSH STRENGTH, MPa
+ 8 fraction, 19% MC	4.02
+10 fraction, 19% MC	5.88
+12 fraction, 19% MC	5.70
+20 fraction, 19% MC	7.49
-20 fraction, 19% MC	9.54
Combined, 19% MC	7.54
Combined, 30% MC	4.30

TABLE 12: RESULTS OF THE 24-HOUR WATER IMMERSION TEST

PELLET IDENTIFICATION	PRESS TEMPERATURE C	% CHANGE UPON SOAKING		COMMENTS
		WEIGHT	THICKNESS	
+ 8 fraction, 19% MC	130	100	100	pellets swollen and disintegrating
	140	100	100	pellets swollen and disintegrating
	150	67.7	83.4	pellets swollen and disintegrating
	160	54.9	47.7	pellets contain large internal splits
	170	47.0	73.3	pellets contain large internal splits
+10 fraction, 19% MC	130	100	100	pellets swollen and disintegrating
	140	100	100	pellets swollen and disintegrating
	150	100	100	pellets swollen and disintegrating
	160	61.9	95.7	pellets swollen and disintegrating
	170	39.5	61.3	pellets contain large internal splits
+12 fraction, 19% MC	130	100	100	pellets swollen and disintegrating
	140	87.0	42.9	pellets swollen and disintegrating
	150	50.4	76.1	pellets contain large internal splits
	160	40.8	57.4	pellets contain large internal splits
	170	27.9	45.1	pellets contain large internal splits
+20 fraction, 19% MC	130	100	100	pellets swollen and disintegrating
	140	100	100	pellets swollen and disintegrating
	150	45.6	58.7	pellets contain large internal splits
	160	27.9	41.3	pellets contain small internal splits
	170	25.5	43.3	pellets contain small internal splits
-20 fraction, 19% MC	130	50.3	61.7	pellets contain large internal splits
	140	32.5	42.9	pellets contain small internal splits
	150	17.2	19.8	pellets contain small internal splits
	160	18.3	20.0	pellets contain small internal splits
	170	16.2	21.1	pellets contain small internal splits
Combined, 19% MC	130	100	100	pellets swollen and disintegrating
	140	66.3	93.3	pellets swollen and disintegrating
	150	40.2	79.2	pellets contain large internal splits
	160	29.7	45.1	pellets contain large internal splits
	170	21.6	31.3	pellets contain small internal splits
Combined, 30% MC	130	100	100	pellets swollen and disintegrating
	140	100	100	pellets swollen and disintegrating
	150	39.7	67.2	pellets contain large internal splits
	160	22.1	28.8	pellets contain small internal splits
	170	17.3	15.4	pellets contain small internal splits

TABLE 13: PROPERTIES OF SOME COMMERCIAL ADHESIVES FOR PELLET BINDING

COMPANY	TYPE OF BINDER	SOLIDS CONTENT	RECOMMENDED ADDITION RATE	RECOMMENDED TEMPERATURE	PRICE	COMMENTS
HERCULES CAN. INC.	1. Crude Tall Oil Rosin				\$0.66/Kg	Have sample
	2. Crude Tall Oil Pitch				\$0.31/Kg	Have sample
DOMTAR	1. Coal Tar Pitch – Liquid			shipped at 160-180°C	\$355/ton 0.39/kg	More expansion than petroleum pitch, no performance difference
	2. Coal Tar Pitch – Solid				\$355/ton 0.39/kg	Available in flake or pellet
	3. Coal Tar Emulsion	30% pitch 20% clay 50% H_2O				
	4. Sludge From Coal Tar Distillation				Very little commercial value	Have sample, quite viscous Was supposed to send sample with specs (never did)
CROWLEY TAR PROD. INC.	Pine Tar	0.99 specific 80°F			\$0.48/Kg	
CANADA GLUE COMPANY INC.	1. Unmodified Animal Glue	depends on glue solution preparation	not specified	not specified	\$1.60/Kg	Can be X-linked to form water-insoluble material using aldehydes or multivalent metal salts
	2. Precatalyzed Animal Glue	40%	not specified	120-175°C (the higher the temp. the better the water resistance	\$4.00/Kg	Can be dissolved in water and when dried under heat, cured to a water resistant form
	3. Dextrine-powdered or liquid	for liquid 26-30%	not specified	not specified	Powdered: \$0.96/Kg Liquid: \$0.59/kg	Can be X-linked to form good H_2O resistance

TABLE 13: PROPERTIES OF SOME COMMERCIAL ADHESIVES FOR PELLET BINDING (Continued)

COMPANY	TYPE OF BINDER	SOLIDS CONTENT	RECOMMENDED ADDITION RATE	RECOMMENDED TEMPERATURE	PRICE	COMMENTS
	4. Caseins -powdered	not specified	not specified	not specified	$5.00/Kg	Can be X-linked
	5. UF resin - Liquid	55±2%	not specified	complete cure in 1 min. or less at 120°C	$0.79.Kg $1.62/Kg catalyst	Must have catalyst added prior to use (10-20%)
	6. UF resin - precatalyzed powder	mixed to approx. 60% solids with water	not specified	complete cure in 1 min. or less at 120°C	$2.20/Kg	Once mixed, has pot life of 2-6 hrs. Water resistant bonds
	7. PVA emulsion	40-45%	not specified	recommended for hot or cold press application	$1.87/Kg	Excellent water resistance once cured, one component adhesive
	8. Emulsified Wax	40-42%	not specified	not specified	$4.00/Kg	
McASPHALT INDUSTRIES LTD.	1. Straight Asphalt			to keep it liquid; 150-175°C		Was going to get back to us to recommend product - (never did)
	2. Sizing Emulsion			to keep it liquid 82°C	$0.44/L	

TABLE 14: SUMMARY OF TEST RESULTS FOR PELLETS PRODUCED WITH VARIOUS ADDITIVES

% Binder Addition (based on moist wood)	Press Temp. °C	Average Density kg/m^3	Average Crush Strength MPa
Jack Pine/Polyethylene (2.26%)	130	1,083 ± 4	3.87
	140	1,088 ± 9	4.45
	150	1,099 ± 7	5.52
	160	1,107 ± 9	5.43
	170	1,115 ± 17	5.28
		Average	4.91
Jack Pine/Polyethylene (3.5%)	130	1,094 ± 9	4.98
	140	1,095 ± 5	4.56
	150	1,108 ± 9	5.35
	160	1,141 ± 28	5.83
	170	1,113 ± 30	5.10
		Average	5.16
Jack Pine/Polyethylene (5.1%)	130	1,073 ± 8	4.06
	140	1,084 ± 7	4.63
	150	1,099 ± 12	5.60
	160	1,110 ± 15	5.74
	170	1,111 ± 13	5.80
		Average	5.16
Jack pine/ Petroleum Vacuum Residue (2%)	130	1,139 ± 3	3.71
	140	1,148 ± 3	4.31
	150	1,163 ± 6	4.73
	160	1,173 ± 11	5.47
	170	1,203 ± 8	5.33
		Average	4.71
Jack pine/ Petroleum Vacuum Residue (5%)	130	1,142 ± 3	3.05
	140	1,155 ± 6	3.83
	150	1,197 ± 8	4.77
	160	1,213 ± 8	5.44
	170	1,241 ± 4	6.47
		Average	4.71
Jack pine/ Tall Oil Pitch (2%)	130	1,108 ± 8	3.04
	140	1,117 ± 8	3.44
	150	1,143 ± 4	4.30
	160	1,161 ± 7	4.76
	170	1,161 ± 16	5.17
		Average	4.14

TABLE 14: SUMMARY OF TEST RESULTS FOR PELLETS PRODUCED WITH VARIOUS ADDITIVES (Continued)

% Binder Addition (based on moist wood)	Press Temp. °C	Average Density kg/m³	Average Crush Strength MPa
Jack pine/ Pine Tar 2%	130	1,136 ± 10	3.60
	140	1,137 ± 9	3.44
	150	1,154 ± 14	3.97
	160	1,192 ± 6	4.51
	170	1,206 ± 19	5.90
		Average	4.28
Jack pine/ Pine Tar 5%	130	1,108 ± 10	2.50
	140	1,133 ± 10	2.98
	150	1,132 ± 10	3.47
	160	1,195 ± 18	4.58
	170	1,186 ± 18	5.14
		Average	3.73
Jack pine/ Waxed Corrugated	130	1,108 ± 5	2.59
	140	1,099 ± 7	3.02
	150	1,134 ± 20	3.51
	160	1,157 ± 13	3.79
	170	1,170 ± 13	4.55
		Average	3.49
Jack pine/polyethylene powder (2%)	130	1,075 ± 6	2.05
	140	1,089 ± 9	2.23
	150	1,087 ± 10	2.47
	160	1,130 ± 10	3.32
	170	1,120 ± 16	3.33
		Average	2.68
Jack pine/polyethylene powder (5%)	130	1,058 ± 13	2.67
	140	1,066 ± 14	3.07
	150	1,078 ± 3	3.04
	160	1,067 ± 17	2.91
	170	1,094 ± 30	3.29
		Average	3.00
Jack pine/rosin (2%)	130	1,078 ± 13	3.76
	140	1,065 ± 18	4.76
	150	1,102 ± 8	4.38
	160	1,107 ± 22	4.84
	170	1,107 ± 17	5.04
		Average	4.56

TABLE 14: SUMMARY OF TEST RESULTS FOR PELLETS PRODUCED WITH VARIOUS ADDITIVES (Continued)

% Binder Addition (based on moist wood)	Press Temp. °C	Average Density kg/m³	Average Crush Strength MPa
Jack pine/rosin (5%)	130	1,077 ± 7	4.28
	140	1,077 ± 11	4.52
	150	1,089 ± 8	5.13
	160	1,106 ± 10	5.91
	170	1,133 ± 31	5.94
		Average	5.16
Jack pine/core pitch (2%)	130	1,108 ± 4	3.77
	140	1,114 ± 9	4.89
	150	1,130 ± 5	5.18
	160	1,138 ± 15	5.75
	170	1,143 ± 21	5.24
		Average	4.97
Jack pine/core pitch (5%)	130	1,114 ± 3	3.74
	140	1,115 ± 3	4.49
	150	1,135 ± 10	5.49
	160	1,143 ± 22	6.67
	170	1,132 ± 13	5.75
		Average	5.23
Jack pine only	130	1,106 ± 14	2.57
	140	1,137 ± 10	3.37
	150	1,146 ± 9	4.51
	160	1,177 ± 15	5.47
	170	1,159 ± 17	5.56
		Average	4.30

TABLE 15

Results of the 24-Hour Water Immersion Test

Pellet Identification	% Binder Addition (based on moist wood)	Moisture Content of Furnish %	Press Temp. °C	% change upon soaking	
				Weight	Thickness
Jack pine/ polyethylene powder	2	30	130	81.4	95.4
			140	47.2	45.1
			150	31.0	26.9
			160	22.5	18.5
			170	18.7	11.8
	5	30	130	36.6	38.9
			140	31.3	41.6
			150	17.4	12.7
			160	12.1	4.8
			170	14.6	4.5
Jack pine/ rosin	2	30	130	71.1	78.6
			140	49.1	61.4
			150	21.0	19.2
			160	15.7	10.1
			170	13.6	9.1
	5	30	130	60.0	71.3
			140	30.8	32.5
			150	25.4	23.6
			160	15.8	13.2
			170	14.9	12.1
Jack pine/ core pitch	2	30	130	86.8	100.0
			140	39.1	41.8
			150	24.3	21.9
			160	17.1	14.0
			170	12.3	9.5
	5	30	130	70.3	90.1
			140	35.9	37.5
			150	27.6	25.4
			160	16.0	13.0
			170	12.9	7.1

TABLE 15

Results of the 24-Hour Water Immersion Test (cont'd)

Pellet Identification	% Binder Addition (based on moist wood)	Moisture Content of Furnish %	Press Temp. °C	% change upon soaking	
				Weight	Thickness
Jack Pine/ Polyethylene film	2.26	30	130	51.8	52.5
			140	38.2	33.0
			150	26.8	20.6
			160	23.5	17.1
			170	17.9	9.8
	3.5	30	130	39.8	39.3
			140	30.8	26.4
			150	17.6	13.7
			160	11.5	9.3
			170	10.6	4.9
	5.1	30	130	50.1	50.3
			140	33.0	29.6
			150	17.8	14.1
			160	13.9	9.0
			170	12.4	5.8
Jack pine/waxed corrugated	17	30	130	61.6	75.4
			140	25.9	27.3
			150	19.7	20.4
			160	13.8	14.9
			170	16.1	21.1
Jack pine/ Petroleum Vacuum Residue	2	30	130	56.1	82.8
			140	37.1	50.5
			150	23.1	27.0
			160	17.0	20.2
			170	11.0	11.7
	5	30	130	>100	>100
			140	78.1	>100
			150	35.6	43.6
			160	19.0	19.9
			170	20.8	26.5

TABLE 15

Results of the 24-Hour Water Immersion Test (cont'd)

Pellet Identification	% Binder Addition (based on moist wood)	Moisture Content of Furnish %	Press Temp. °C	% change upon soaking	
				Weight	Thickness
Jack pine/ Tall Oil Pitch	2	30	130	55.6	64.4
			140	35.6	42.8
			150	26.5	31.5
			160	13.3	12.2
			170	11.4	9.3
Jack pine/ Pine Tar	2	30	130	>100	>100
			140	94.6	>100
			150	48.1	71.8
			160	37.1	68.1
			170	24.9	55.6
	5	30	130	83.2	92.7
			140	49.7	76.3
			150	31.6	37.8
			160	22.6	35.8
			170	20.5	29.8
Jack pine only	-	30	130	>100	>100
			140	>100	>100
			150	39.7	67.2
			160	22.1	28.8
			170	17.3	15.4

TABLE 16

Average Pellet Crush Strength vs. Type of Binder and Binder Content

Binder Identification	% Binder Addition	Average Crush Strength, MPa
Polyethylene Powder	2	2.68
	5	3.00
Rosin	2	4.56
	5	5.16
Core Pitch	2	4.97
	5	5.23
Waste Polyethylene Film	2.26	4.91
	3.5	5.16
	5.1	5.16
Waxed Corrugated	17	3.49
Jack Pine Only	-	4.30
Pine Tar Blend	2	4.28
	5	3.73
Petroleum Vacuum Residue	2	4.71
	5	4.71
Tall Oil Pitch	2	4.14

TABLE 17

Comparison of Pellets made from Jack Pine Wood at Moisture Contents of 19% and 30% with a Polyethylene Powder Addition of 2.7% O.D.Basis

Moisture Content of furnish (%)	Press Temp. °C	Average Density kg/m³	Average Crush Strength, MPa	% Change upon Soaking Weight	Thickness
19	130	1179 ± 21	3.89	71.2	92.7
	140	1182 ± 16	4.06	50.5	63.7
	150	1193 ± 25	4.47	36.1	43.5
	160	1204 ± 15	4.27	25.9	35.6
	170	1222 ± 12	4.28	19.4	25.4
30	130	1075 ± 6	2.05	81.4	95.4
	140	1089 ± 9	2.23	47.2	45.1
	150	1087 ± 10	2.47	31.0	26.9
	160	1130 ± 10	3.32	22.5	18.5
	170	1120 ± 16	3.33	18.7	11.8

TABLE 18

RESULTS OF THE HEATING VALUE ANALYSIS

Sample Identification	Heating Value (1)		
	Cal/g	BTU/lb	MJ/kg
1. Laboratory Pellets			
100% Jack pine (Pj)	5126	9228	21.45
Pj + 5% core pitch	5333	9600	22.31
Pj + 5% rosin	5188	9339	21.70
Pj + 5% pine tar	5303	9546	22.18
Pj + 3.5% waste polyethylene	5385	9694	22.53
Pj + 5% waste polyethylene	5523	9942	23.11
2. Extruded Pellets			
100% Pj	5030	9055	21.04
Pj + 2% polyethylene	5180	9325	21.67
Pj + 5% polyethylene	5306	9552	22.20
Commercial "Energex"	4613	8303	19.30

NOTE

(1) Results corrected for moisture, but not for ash or sulphur.

TABLE 19

PHYSICAL CHARACTERISTICS OF THE EXTRUDED PELLET SAMPLES

Parameter	Units	Test Results for specified sample		
		100% Pj	Pj + 2% Polyethylene	Pj + 5% Polyethylene
Pellet Density (oven-dry basis)	kg/m^3	1333	1300	1271
Moisture Content (oven-dry basis)	%	6.6	8.7	6.8
Heating Value (dry)	MJ/kg	21.04	21.67	22.20
	BTU/lb	9055	9325	9552
Loss on Shake Test	wt.%	3.6	2.5	1.5

FIGURE 3: SIZE DISTRIBUTION OF COMMINUTED JACK PINE WOOD

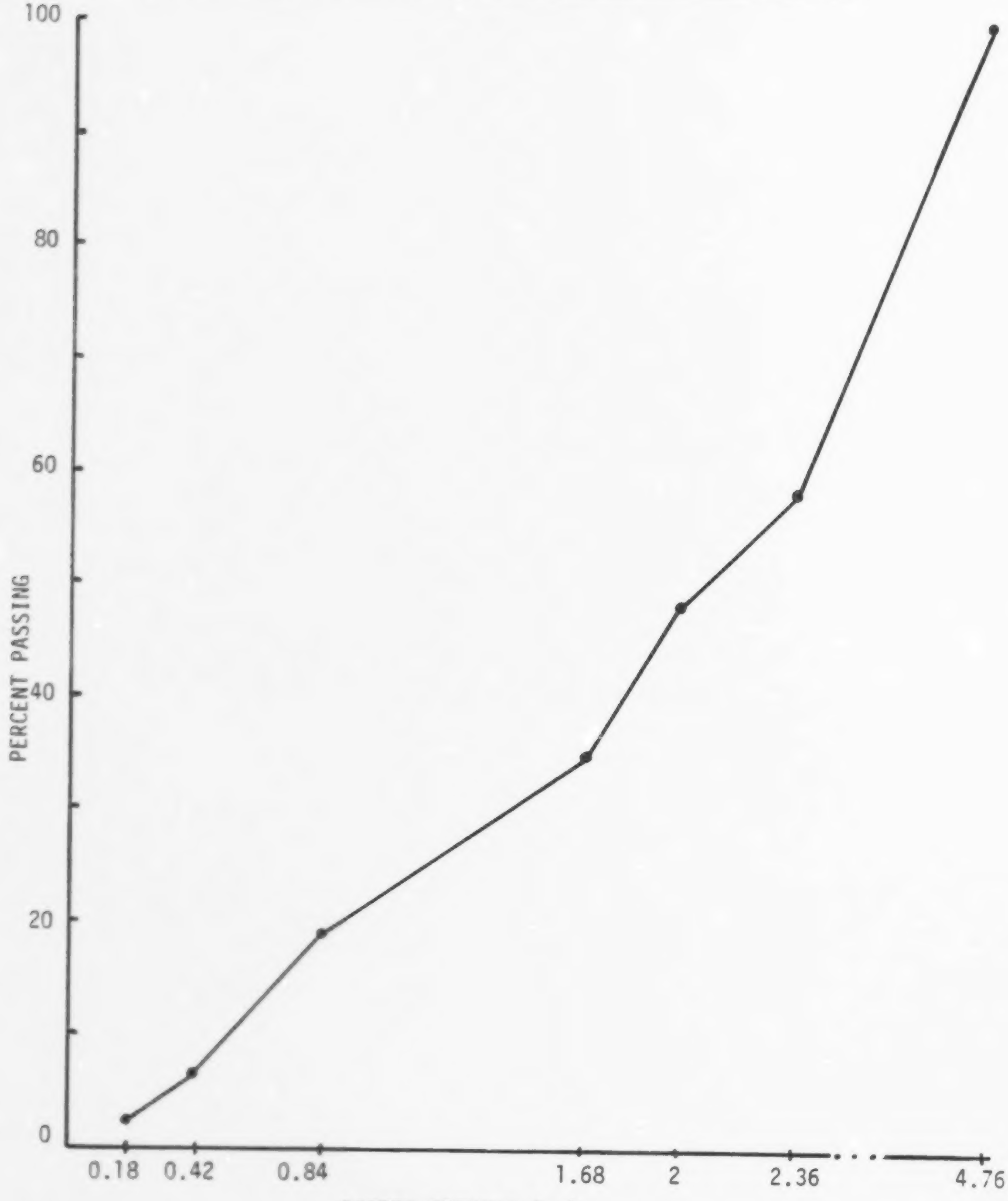
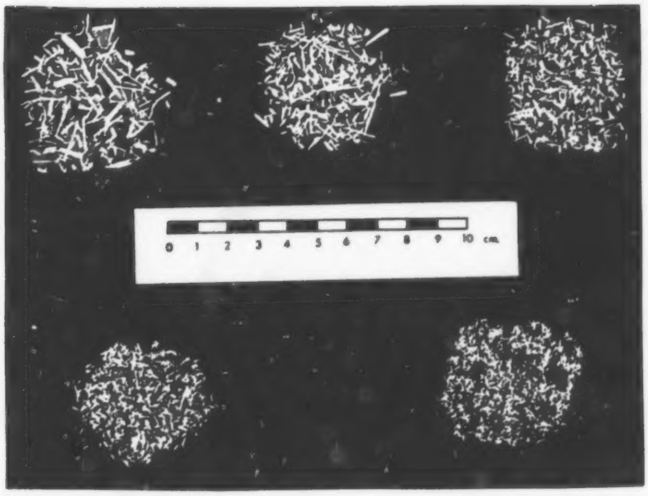


FIGURE 4: APPEARANCE OF COMMINUTED JACK PINE FRACTIONS USED IN MAKING LABORATORY-PRESSED PELLETS

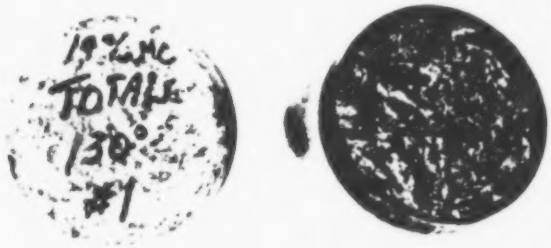


Top Row (left to right): +8 fraction, +10 fraction, +12 fraction

Bottom Row (left to right): +20 fraction, -20 fraction

FIGURE 5: PHOTOGRAPHS SHOWING THE EFFECTS OF PARTICLE SIZE AND PRESS TEMPERATURE ON PELLET APPEARANCE

(a) Combined fraction
Left: 19% MC, 130°C / Right: 30% MC, 170°C



(b) +8 Fraction
Left: 19% MC, 130°C / Right: 19% MC, 170°C

(c) -20 Fraction
Left: 19% MC, 170°C / Right: 19% MC, 130°C

FIGURE 6

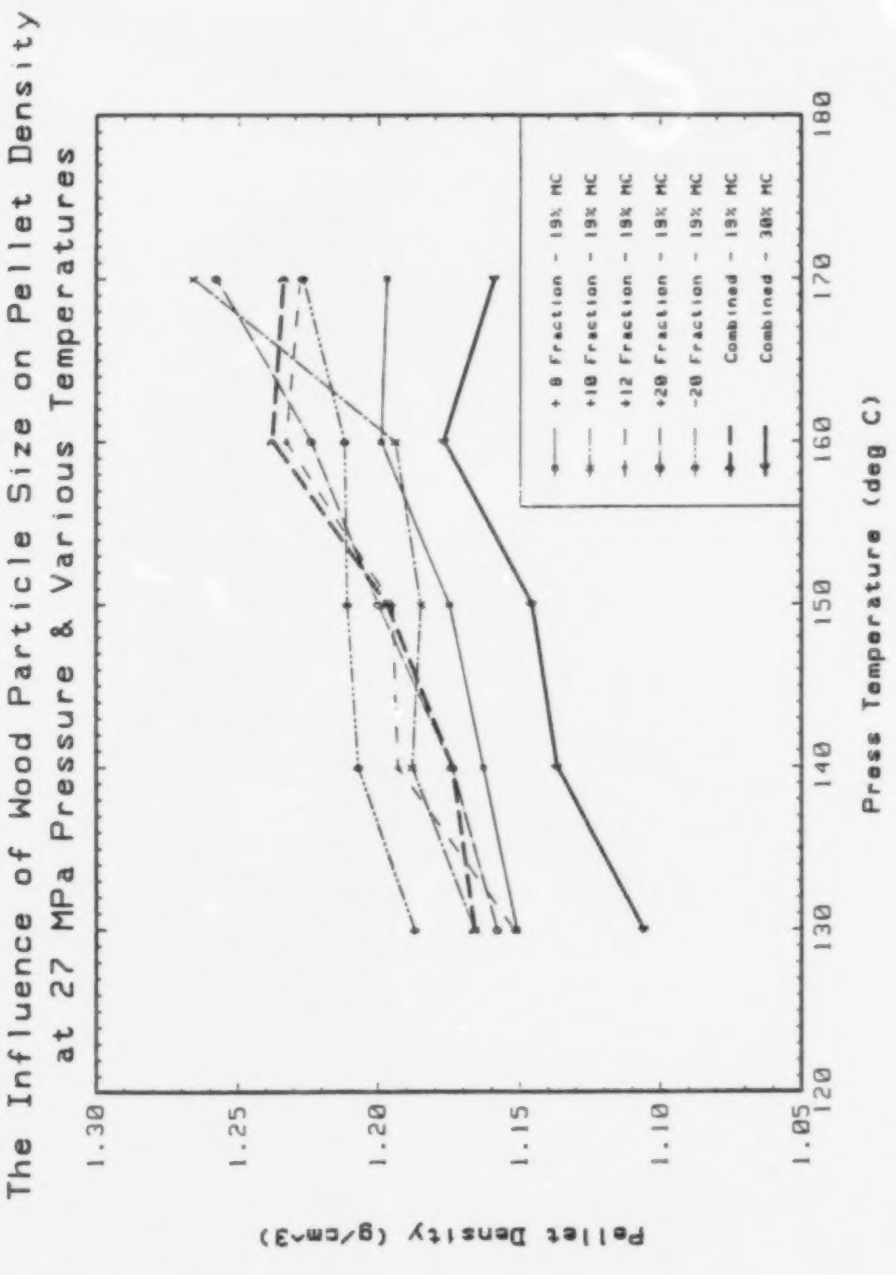

The Influence of Wood Particle Size on Pellet Density
at 27 MPa Pressure & Various Temperatures
Pellet Density (g/cm^3)
1.30
1.25
1.20
1.15
1.10
1.05
Press Temperature (deg C)
120
130
140
150
160
170
180
+ 8 Fraction - 19% MC
+10 Fraction - 19% MC
+12 Fraction - 19% MC
+20 Fraction - 19% MC
-20 Fraction - 19% MC
Combined - 19% MC
Combined - 30% MC

FIGURE 7

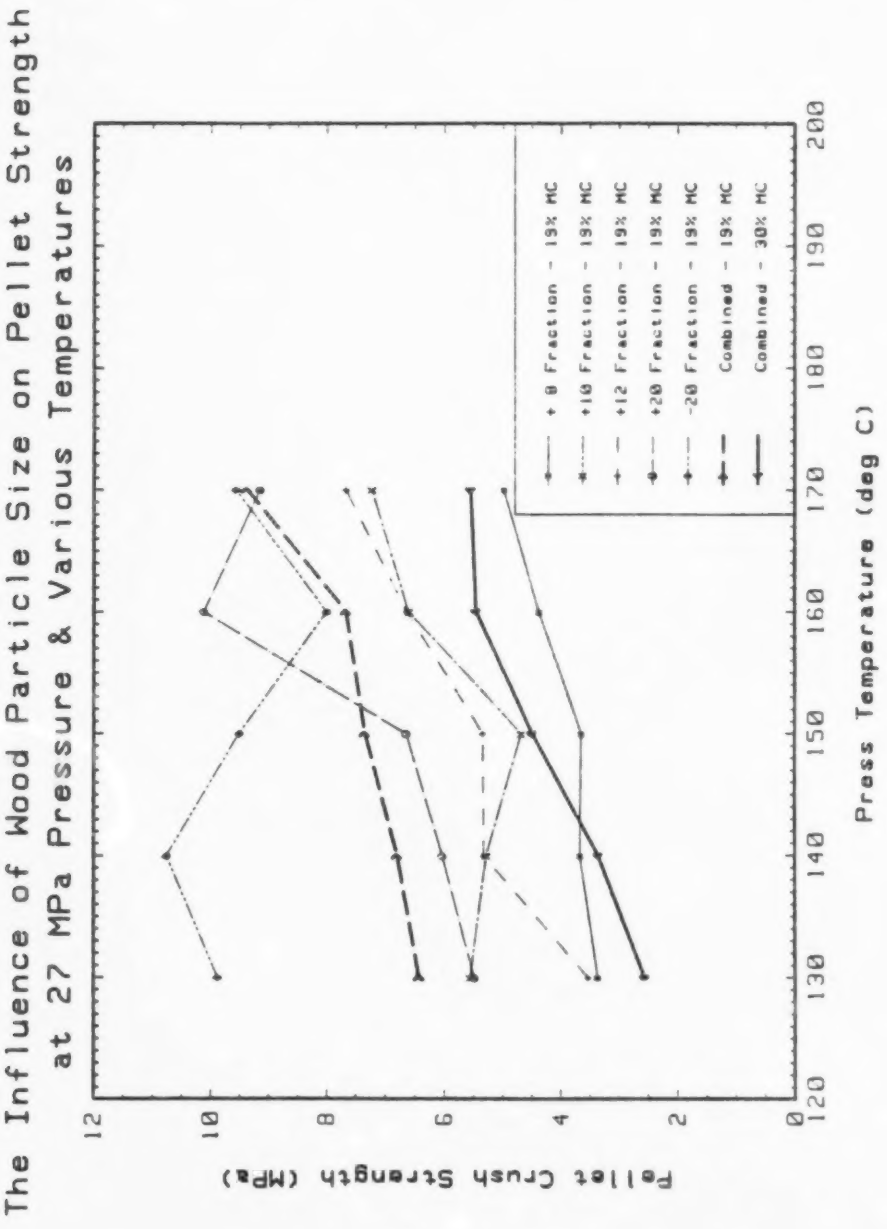

The Influence of Wood Particle Size on Pellet Strength
at 27 MPa Pressure & Various Temperatures
Pellet Crush Strength (MPa)
0
2
4
6
8
10
12
Press Temperature (deg C)
120
130
140
150
160
170
180
190
200
+ 8 Fraction - 19% MC
+10 Fraction - 19% MC
+12 Fraction - 19% MC
+20 Fraction - 19% MC
-20 Fraction - 19% MC
Combined - 19% MC
Combined - 30% MC

FIGURE 8

The Influence of Wood Particle Size on Pellet Moisture Stability at Various Temperatures & 27 MPa Pressure

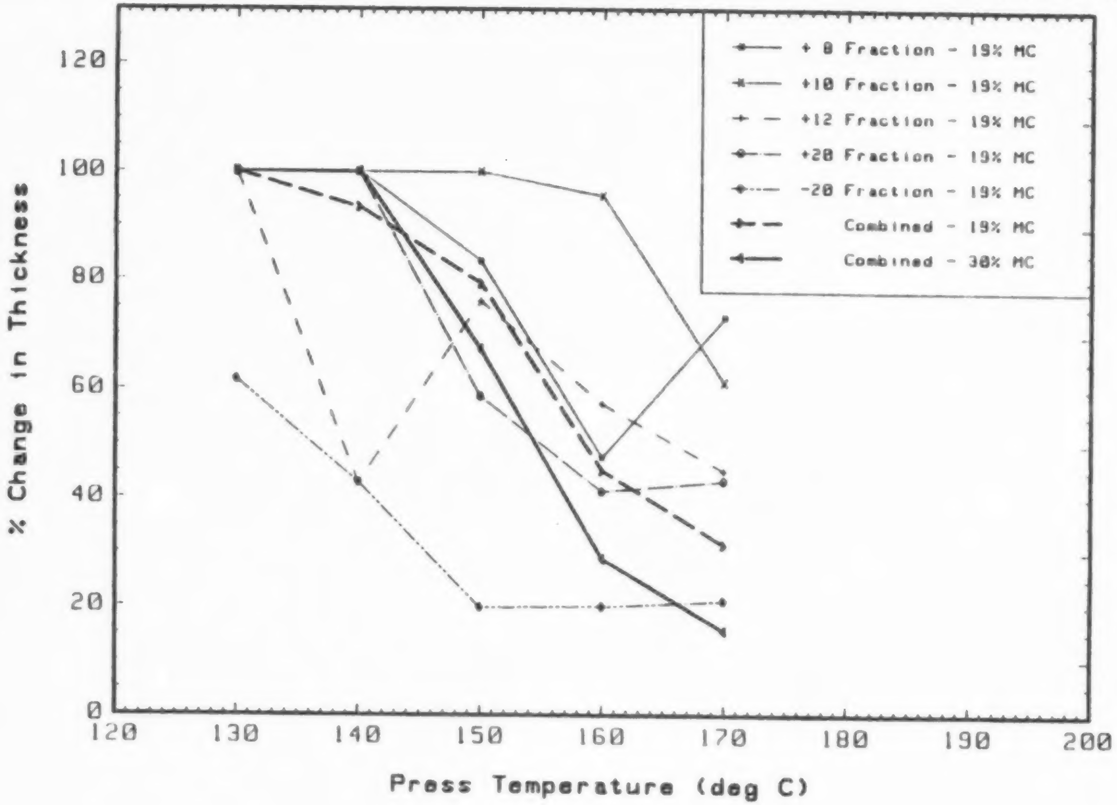


FIGURE 9: THE APPEARANCE OF PELLETS AFTER THE 24-HOUR WATER IMMERSION

(a) Pellets from -20 fraction
19% MC, 150°C

(b) Pellets from +12 fraction
19% MC, 160°C

(c) Pellets from Combined Wood
19% MC, 130°C

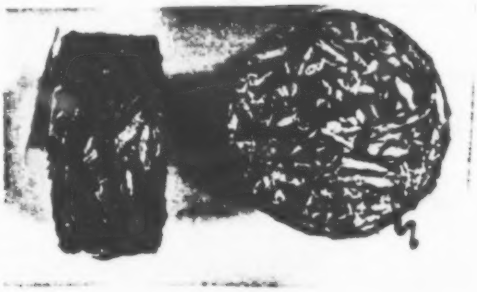


FIGURE 10

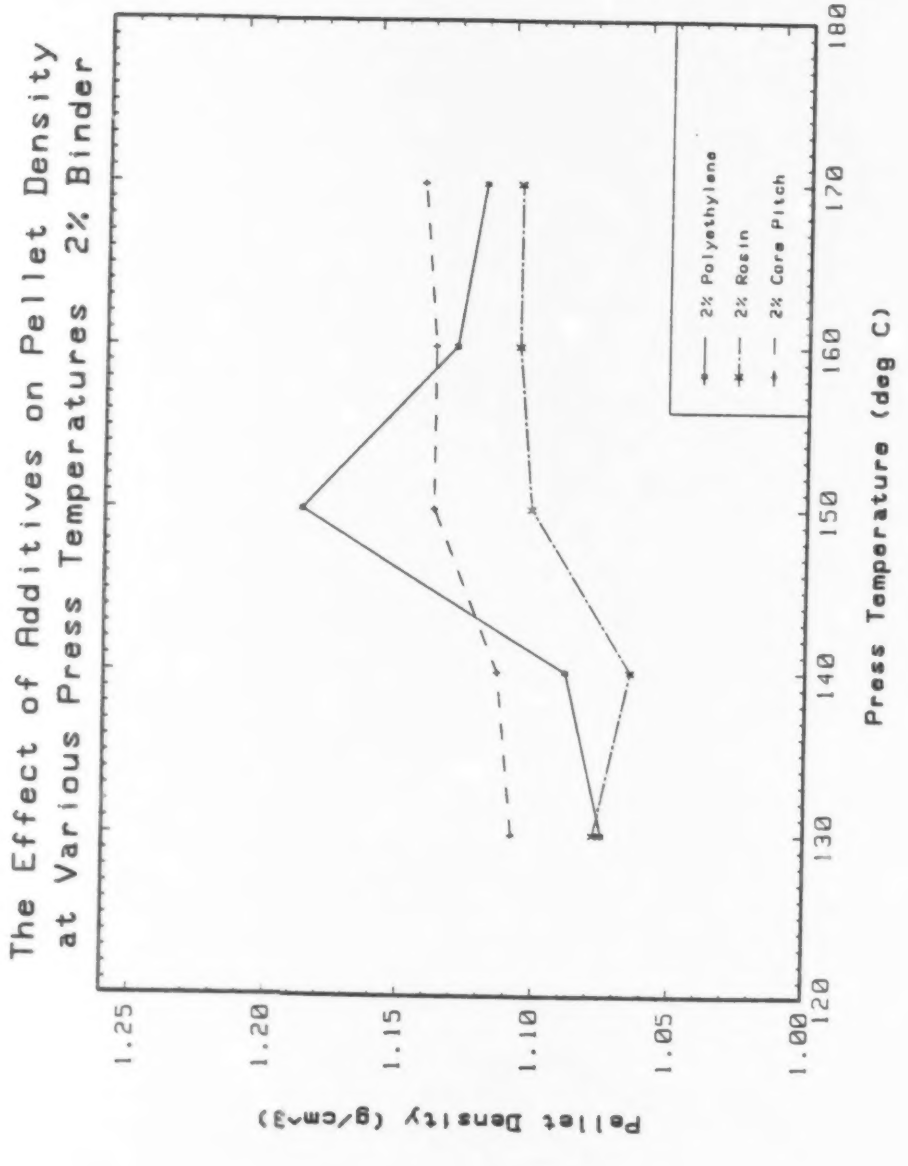

The Effect of Additives on Pellet Density
at Various Press Temperatures 2% Binder
Pellet Density (g/cm^3)
1.25
1.20
1.15
1.10
1.05
1.00
Press Temperature (deg C)
120
130
140
150
160
170
180
2% Polyethylene
2% Rosin
2% Core Pitch

FIGURE 11

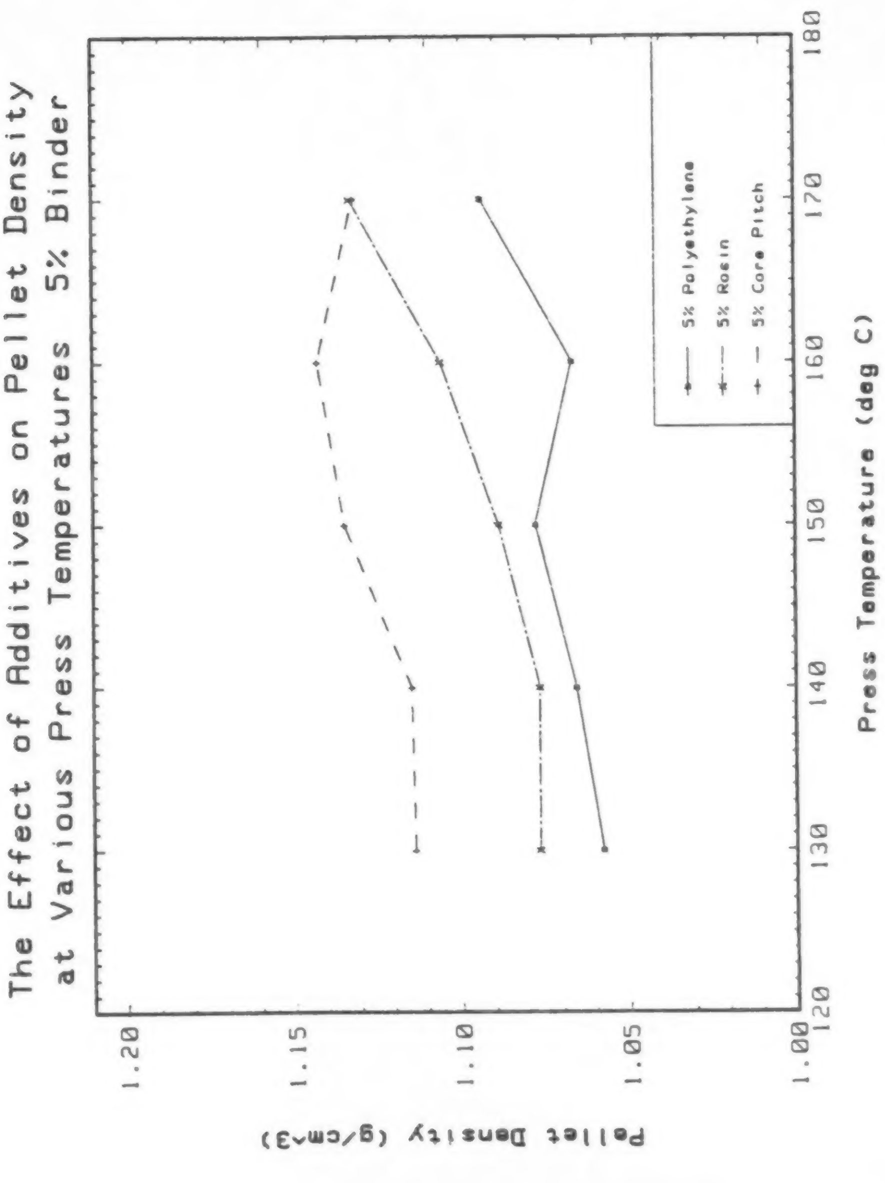

The Effect of Additives on Pellet Density
at Various Press Temperatures 5% Binder
Pellet Density (g/cm^3)
1.20
1.15
1.10
1.05
1.00
120
130
140
150
160
170
180
Press Temperature (deg C)
5% Polyethylene
5% Rosin
5% Core Pitch

FIGURE 12

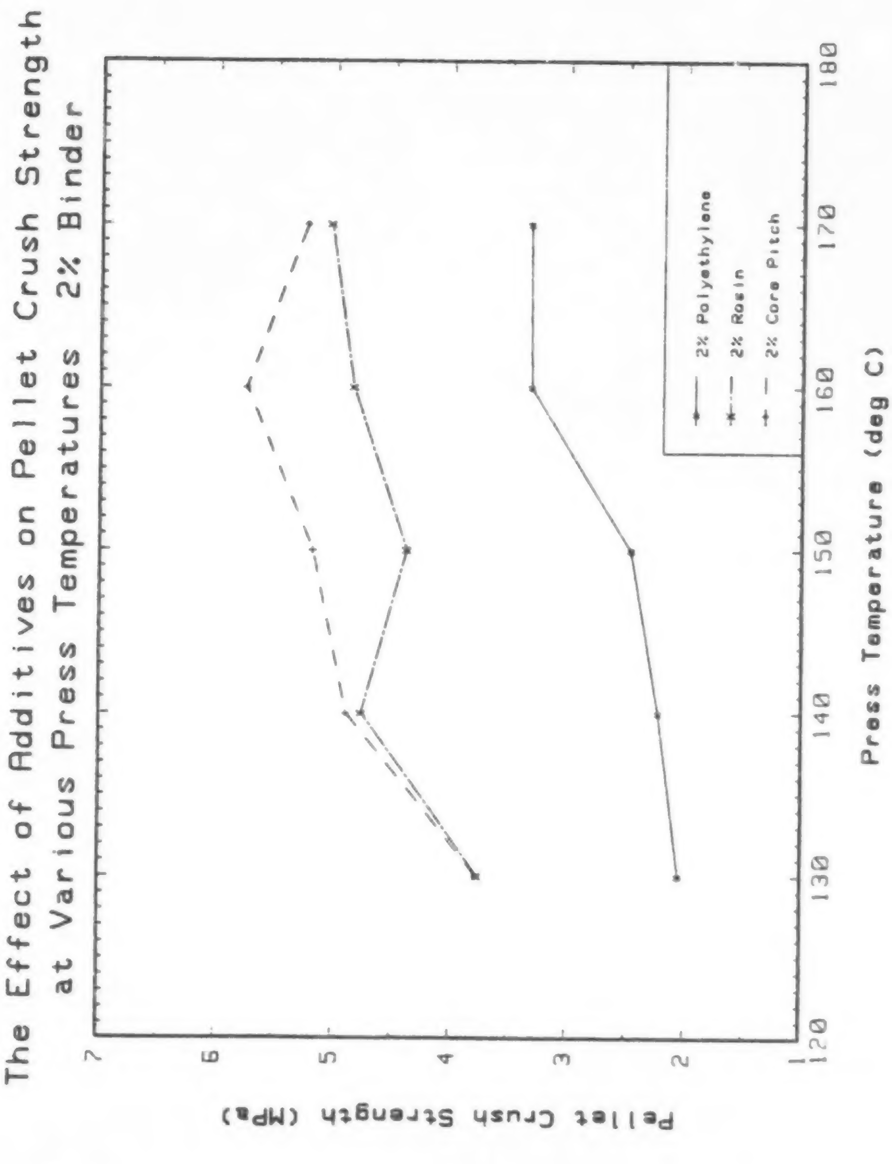

The Effect of Additives on Pellet Crush Strength
at Various Press Temperatures 2% Binder
Pellet Crush Strength (MPa)
1
2
3
4
5
6
7
Press Temperature (deg C)
120
130
140
150
160
170
180
2% Polyethylene
2% Rosin
2% Core Pitch

FIGURE 13

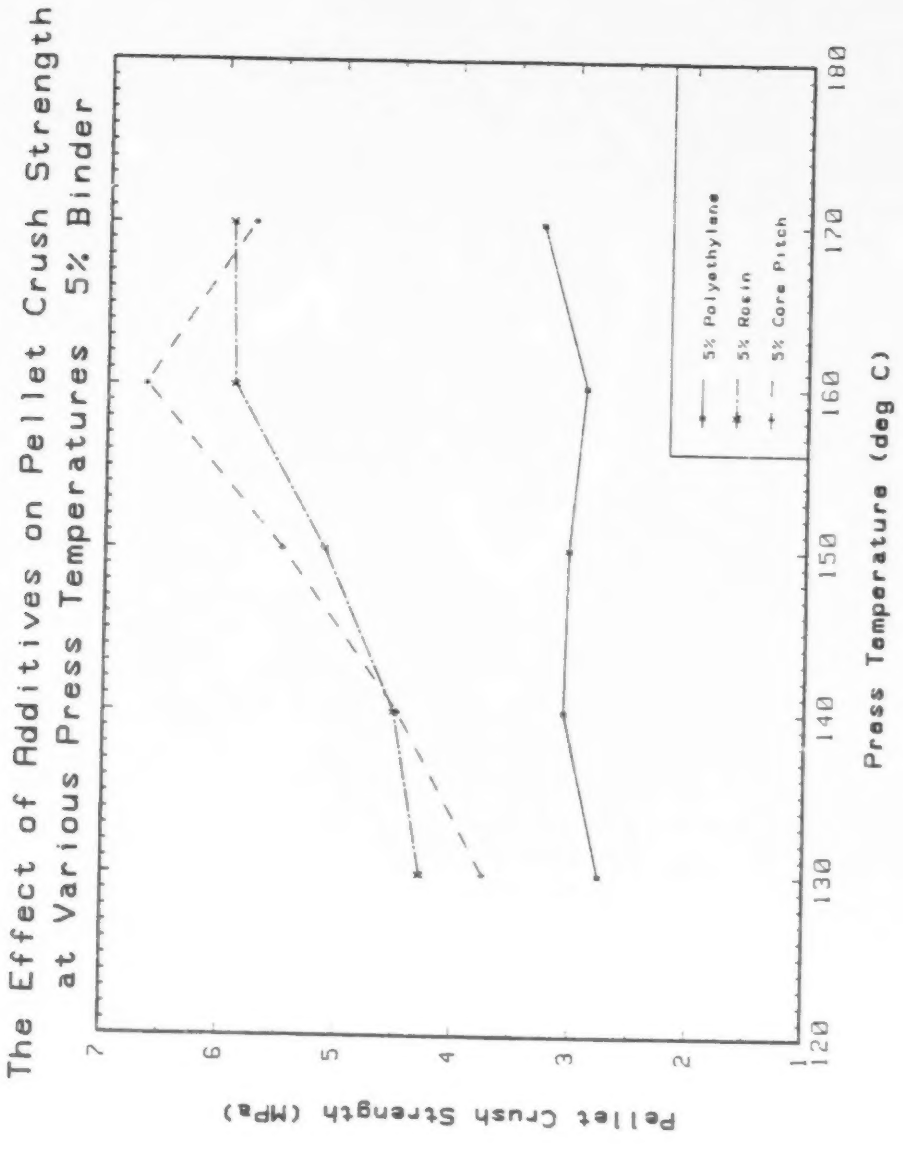
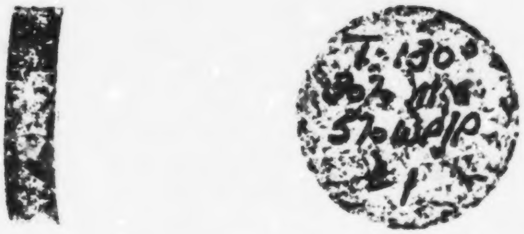

The Effect of Additives on Pellet Crush Strength
at Various Press Temperatures 5% Binder
Pellet Crush Strength (MPa)
7
6
5
4
3
2
1
120
130
140
150
160
170
180
Press Temperature (deg C)
5% Polyethylene
5% Rosin
5% Core Pitch

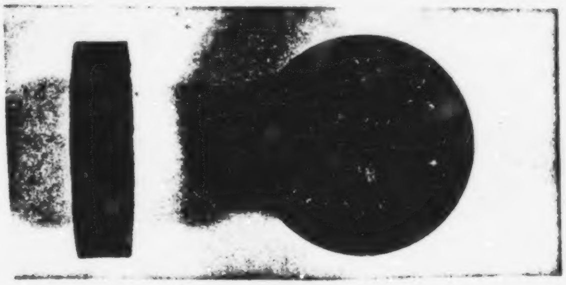
FIGURE 14: THE APPEARANCE OF PELLETS MADE WITH VARIOUS ADDITIVES

(a) 5% Waste Polyethylene Film



Left: 30% MC, 160°C / Right: 30% MC, 130°C

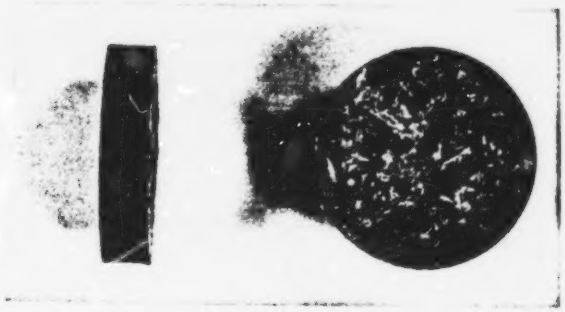
(b) 5% Polyethylene Powder



Left: 30% MC, 170°C / Right: 30% MC, 130°C

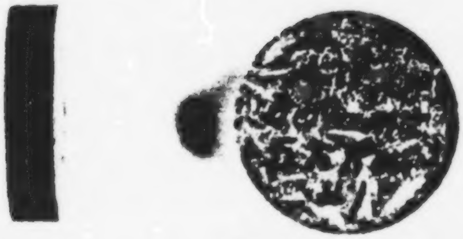
FIGURE 14: THE APPEARANCE OF PELLETS MADE WITH VARIOUS ADDITIVES (Continued)

(c) 20% Waxed Corrugated



Left: 30% MC, 170°C / Right: 30% MC, 130°C

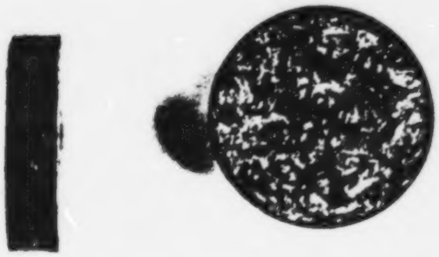
(d) 5% Rosin



Left: 30% MC, 170°C / Right: 30% MC, 130°C

FIGURE 14: THE APPEARANCE OF PELLETS MADE WITH VARIOUS ADDITIVES (Continued)

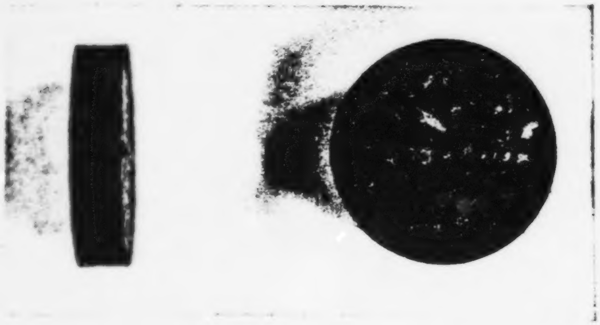
(e) Pellets Made With 5% Core Pitch



Left: 30% MC, 170°C / Right: 30% MC, 130°C

FIGURE 15: THE APPEARANCE AFTER WATER IMMERSION OF PELLETS PRESSED AT DIFFERENT TEMPERATURES WITH VARIOUS BINDERS

(a) Pellets Made With 5% Waste Polyethylene Film



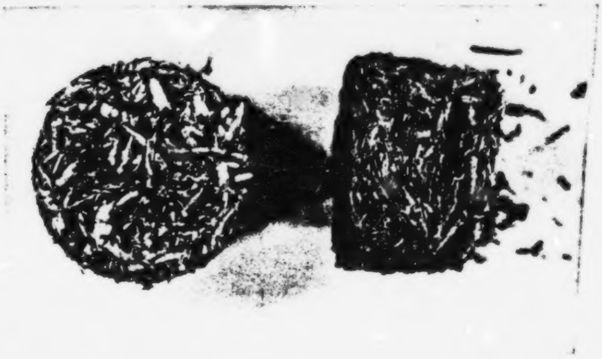
30% MC, furnish, maximum press temperature of 130°C

(b) Pellets Made With 5% Polyethylene Powder

30% MC, furnish, maximum press temperature of 170°C

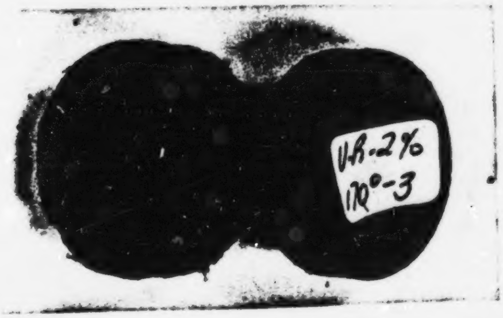
FIGURE 15: THE APPEARANCE AFTER WATER IMMERSION OF PELLETS PRESSED AT DIFFERENT TEMPERATURES WITH VARIOUS BINDERS (Continued)

(c) Pellets Made With 2% Pine Tar Pitch



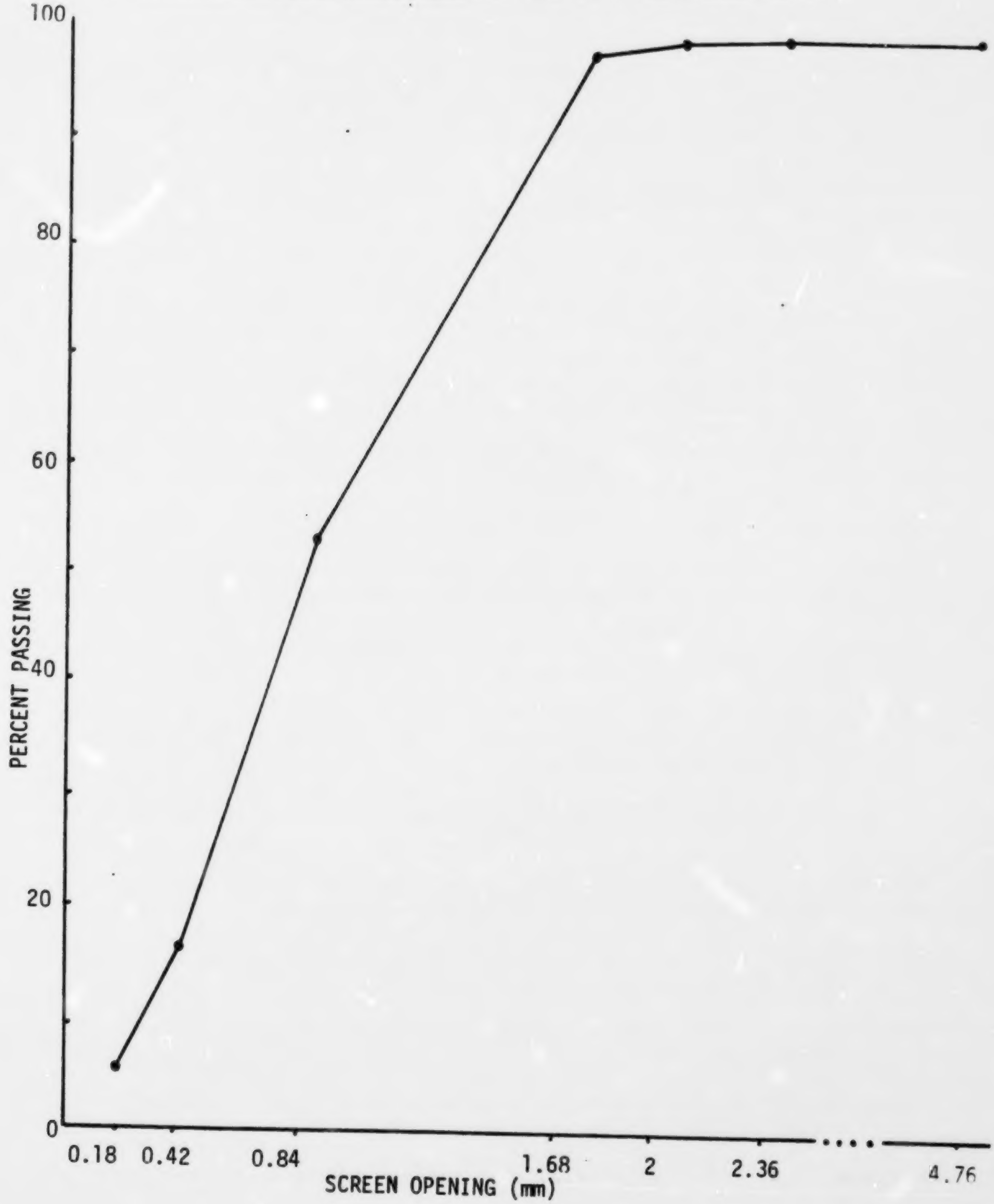
30% MC, furnish, maximum press temperature of 130°C

(d) Pellets Made with 2% Vacuum Resid



Left: 30% MC, 130°C / Right: 30% MC, 170°C

FIGURE 16: SIZE DISTRIBUTION OF HAMMERMILLED JACK PINE WOOD



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DEVELOPMENT OF A MOISTURE RESISTANT DENSIFIED SOLID FUEL FROM FOREST BIOMASS

PART II

COMPARATIVE COMBUSTION TESTS OF COMMERCIALLY AVAILABLE AND WATER REPELLENT DENSIFIED FUEL PELLETS IN A WOOD FIRED FURNACE TO ESTABLISH TRENDS FOR OVERALL FUEL PERFORMANCE VERSUS FUEL TYPE

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EXECUTIVE SUMMARY

The Ontario Research Foundation carried out a project for Energy, Mines and Resources Canada concerning development of a moisture resistant densified solid fuel from forest biomass. The developmental work carried out is described in Part I of this report. Part II reports on the comparative combustion tests carried out on the fuel pellets that were developed, and on commercially available biomass pellets.

The objective of this work was to compare the combustion characteristics of the pellets that were developed in the program against commercially available pellets (Energex pellets).

Testing was carried out in ORF's solid fuel combustion system test facility. A 150 MegaJoule per hour (MJ/h) residential combination solid fuel/oil furnace was used for the program. Instrumentation was used to gather the following information:

- Charge weight of fuel
- Weight of ash and coals at end of test
- Flue analysis for CO_2, CO, O_2, NO_x, particulates and Total Hydrocarbons (THC)
- Flue temperature
- Air flow rate and temperature rise across furnace heat exchanger
- Rate of fuel consumption
- Furnace efficiency with No. 2 fuel oil (stack loss method)

A procedure for comparison of the fuel pellets was developed based on a CSA draft standard for evaluation of solid fuel appliances, and on trial and error testing. The procedure involved operation of the furnace on No. 2 fuel oil for about an hour, until the furnace had warmed up to approximately steady state. A 4.5 kg charge of pellets was then loaded into the solid fuel combustion chamber, and ignited with a natural gas burner placed under the grate. Once combustion of the pellets was self sustaining, the burner was removed. A second charge of 4.5 kg of pellets was added when the flue gas temperature dropped to about 140°C. A third charge of 4.5 kg was added after the second charge had burned and the flue temperature had again dropped to 140°C. The test was terminated when the flue temperature dropped to 115°C after the final charge had burned.

Tests were carried out on 3 developed pellets plus the base fuel. These are described as follows:

Base fuel - Energex pellets
100% Jack pine pellets
98% Jack pine plus 2% polyethylene
95% Jack pine plus 5% polyethylene

All of the pellets were approximately the same size. The pine pellets had an ash content of about 0.3% as compared to about 4 to 5% for the Energex pellets. The results of the combustion tests are contained in the summary table. The pine pellets were as easy or easier to ignite than the Energex pellets. The total hydrocarbon content of the flue gases was considerably lower for the pine pellets than for the Energex pellets. This would indicate more complete combustion of the pine pellets, with less creosote production. There was no significant change in the furnace efficiency for the pellets tested.

Summary Table

Results of comparative combustion tests of commercial and improved biomass fuel pellets in the 150MJ Wood / Coal / Oil Furnace to establish trends in the overall fuel performance versus fuel type.

Test Fuels: A - Furnace fuel oil used at the beginning and at the end of the test program
B - 'ENERGEX' commercially available biomass fuel pellets - reference test
C - 100% pine (jack) - base test
D - 98% pine (jack) + 2% polyethylene
E - 95% pine (jack) + 5% polyethylene
} the best three of the improved pellets

PARAMETERS (Average of the last two of the three loads with each load = 4.5 kg)																
COMBUSTION								EMISSIONS							HEAT TRANSFER	
FUEL	BURN RATE kg/h	EXCESS AIR % (MIN)	ADIABATIC FLAME TEMP. °C (MAX)	STACK TEMP. °C	O_2 %	CO_2 % (MAX)	EFF. %	① CO PPM	② THC PPM	③ SO_2 PPM	④ NO_x PPM	⑤ PART. CONC. mg/M³	PART. EMISSION RATE g/h	SUM*	HEAT OUTPUT MJ/h	EFF. %
A1	3.59	69***	1358	265	8.9	8.6	n/m	1.0	n/m	n/m	n/m	n/m	n/m	n/m	113	76 (76.2)**
A2	3.64	73***	1331	247	9.2	8.3	n/m	1.0	n/m	n/m	n/m	n/m	n/m	n/m	111	73.4 (76.5)**
B	5.73	372 (163)	568 (916)	181	16.8	4.2 (7.4)	66.0	1474	538	7.5	34	175	14	2228*	38.7	53.4
C	6.76	230 (48)	778 (1516)	222	14.9	6 (13.5)	84.5	1472	128	9.6	25	426	41	2061*	57.2	50.3
D	6.02	300 (76)	672 (1333)	215	15.7	5 (11.4)	91.1	1331	240	6.6	19	265	24	1861*	45.8	49.8
E	5.78	268 (101)	732 (1215)	212	15.6	5.2 (9.6)	89.7	1594	275	5.1	20	385	32	2279*	46.3	50.2

* Emission number was created for this study only and is a sum of parameters (1 + 2 + 3 + 4 + 5)

** Efficiency by the flue gas heat loss method

*** Based on O_2 reading

n/m not measured

The conclusion from the test program was that the combustion characteristics of the developed fuel pellets were equal or superior to those of the commercially available Energex fuel pellets in all aspects considered.

It is recommended that combustion tests be carried out using an industrial type burner, and that methods for continuous monitoring of fuel moisture content and quality be investigated.

1.0 INTRODUCTION

In April of 1985 ORF started this project to develop densified biomass fuel pellets (DBFP) superior to those presently available on the market in structual integrity and water absorption.

Strong water repellent pellets maintain their heating value longer during storage and transportation and are more desirable as a boiler fuel due to their lower dust content.

Of the several types of improved pellets produced at ORF, the two best jack pine fuels with and one without polyethylene - (base fuel) were evaluated in the combustion tests.

This report describes testing of improved biomass fuel pellets in a 150 MegaJoule/hour (MJ/h) combustion furnace that was designed to burn wood, coal or oil. It also provides information on reference combustion tests of commercially available biomass fuel pellets that were carried out to establish trends in the overall fuel performance versus fuel type. Further, it provides information on the reference combustion tests with No. 2 fuel oil. To accentuate differences in combustion characteristics of different biomass fuel pellets, testing was carried out under least favourable firing conditions encompassing non-steady state and batch loaded appliance operation.

2.0 OBJECTIVE

The main objective of the comparative combustion tests of improved and commercially available densified biomass fuel pellets in a wood fired furnace was to establish trends for overall fuel performance versus fuel type.

3.0 BACKGROUND

This short background information encompasses an overview of utilization of biomass fuel and a technical discussion of biomass combustion.

3.1 Overview of Utilization of Solid Fuels

Biomass is a fuel of the future. Its long term use is inevitable due to either worldwide upheavals in the fossil fuels supply market and/or escalating price of fossil fuels caused by a worldwide overconsumption and depletion.

Biomass contains little sulphur and represents an important but underutilized renewable source of energy on this continent. Wood and forest product residues, grasses, agricultural crops and their residues, animal wastes, and other biomass resources currently supply nearly 3.5% [1] of the total energy consumption in the U.S. and 5% in Canada. As an abundant, renewable, domestic energy source, biomass can help Canada, and particularly Ontario and Atlantic provinces, to reduce their dependence on imported oil and natural gas.

One of the main obstacles that restricts wider use of biomass in industry is:

- Lack of biomass fuel that has uniform physical and chemical characteristics and high energy density to alleviate distribution costs, and resistance to moisture absorption to reduce storage costs.

In order to overcome this obstacle, government and industry have joined efforts in recent years to develop new technologies to utilize biomass fuel in an environmentally acceptable fashion. The fruit of the consolidated effort is biomass pelletization processes.

Biomass pelletization is a densification process and is another method of circumventing many of the biomass distribution and material handling problems at the point of use, improving the energy density of the fuel, and obtaining uniform moisture content and size distribution.

3.2 Technical Discussion of Biomass Combustion

Due to the complex composition of wood and relatively large pieces that are used in typical wood-fired appliances, the combustion process is inherently heterogeneous. The major chemical components of wood are cellulose, hemicelluloses and lignin, which are essentially compounds of carbon, hydrogen and oxygen. When wood is heated many chemical compounds are produced in the form of gases and liquid droplets (tars). Depending on the size and shape of the solid fuel, say a (wood) log, uneven temperature distribution usually occurs and consequently very complex chemical reactions take place at different parts of the wood. Wood combustion, therefore, involves many phases occurring at different times and at different physical locations within the combustion zone.

For simplicity we may divide these complex combustion processes into three broad spectrum phases as follows:

Phase I - Dehydration and Partial Pyrolysis

The first phase is primarily an endothermic process that takes place at nominal temperatures up to 290°C. Water vapour, tar and other volatiles are produced, but these products are not ignitable at this temperature.

Phase II - Pyrolysis and Partial Combustion

As the surface temperature exceeds 290°C, pyrolysis becomes more vigorous. The majority of gases and tars evolved will still not ignite and sustain combustion. However, partial combustion may occur if adequate oxygen is available and the ignition temperature (approximately 600°C) is reached due to other established flames or by burning charcoal from already ignited wood.

Phase III - Sustained Combustion

Sustained combustion of evolved gases, tars and the charcoal occurs in the presence of adequate oxygen when the combustion zone temperature exceeds 600 - 650°C. As the carbon (along with hydrogen and oxygen) in the charcoal is consumed, the remaining elements that do not form gaseous compounds are left as ash.

All of these various stages of pyrolysis and burning are often taking place simultaneously in each piece of wood. However the combustion process of a large log having low surface-to-volume ratio when fed to the furnace on a batch basis will be more heterogeneous than combustion of small wood pellets fed continuously to the combustion apparatus.

Except for higher ash content, combustion of pelletized biomass, when fed on a non-batch basis to the combustor, will have virtually the same characteristics as fossil fuels.

4.0 COMBUSTION TEST FACILITY

Combustion tests were carried out in the ORF's Test and Development Facility for solid fuel appliances. A 150 MJ/h combination furnace designed to burn either wood, coal or oil was installed in the facility. The furnace was mounted on a load cell so that the rate of combustion of wood pellets could be monitored. A lever system was developed which suspends the furnace to be tested at one end, and a strain gauge load cell is mounted at the opposite end to measure the weight and the rate of solid fuel consumption. Linearization, conversion and recording of the output signal was accommodated through the computerized data acquisition system. Since the appliance efficiency was not the main objective of the test program, (the furnace was used as a tool rather than the test object), and, due to the limited budget, the test program was carried out without the use of the flue calorimeter that was developed for the continuous instantaneous heat loss method for determining solid fuel appliance efficiency.

Figure 1 shows the Facility and Figure 2 the block diagram of the Test and Development Facility for Solid Fuel Combustion System and the various parameters that were monitored during a test cycle.

Type T and type K thermocouples were used to measure the various temperatures as indicated in Figure 2. Type K thermocouples were used on all high temperature measurements (flue gas) due to their extended high temperature accuracy range and their non-corrosive characteristics especially when used with high sulphur content fuels. Thermocouple reference junction compensation and linearization were performed through the data acquisition system.

5.0 COMBUSTION AND EMISSION TESTING EQUIPMENT

Monitoring instrumentation used in the test program consisted of both continuous on-line and manual types. The instrumentation used is briefly described below.

Two independent computerized systems were used for the continuous on-line analysis. The first was used for combustion process control and monitoring of fuel consumption and furnace heat output. The second, ORF's Mobile Source Monitoring Laboratory (MSML) shown in Figure 3 was used for continuous gas analysis. Sample extraction, conditioning and analysis methodologies are described below.

An air eductor system in the MSML provided a sample flowrate of about 15 to 20 litres per minute. The total hydrocarbon analyzer drew off a portion of this unconditioned sample for analysis. Another portion was drawn through a conditioning system consisting of a vertical by-pass filter, a refrigeration dryer and a permeation dryer. The clean, dry sample was then distributed to the remaining analyzers. The type of analyzers used were as follows:

5.1 Combustion Parameters

Oxygen

A Taylor Servomex, Model OA272, and Beckman Model 755, Paramagnetic Oxygen Analyser were used for oxygen measurement. The instruments were calibrated routinely using a certified calibration gas throughout the test program to ensure consistency.

Carbon Monoxide and Carbon Dioxide

Beckman Model 864 and Horiba AIA-23 and AIA-23AS Non-Dispersive Infra-red Analysers were used to monitor CO_2 and CO concentrations. Calibration gases were employed to calibrate the instruments on a routine basis.

5.2 Emission Parameters

Total Hydrocarbons Analyser

The instrument used was a Ratfisch, Model RS55, Total Hydrocarbon Analyser equipped with a flame ionization detector (FID). The unit, with its own heated pump, was installed upstream of the gas conditioning system since gas cooling and moisture removal were not required for THC analysis. Zero air and propane standard gases were individually introduced into the instrument for zero and calibration checks. These checks were performed at frequent intervals throughout each series of tests.

Sulphur Dioxide

An Ultraviolet Analyser, Western Research Model 721A, was used to measure SO_2 concentration in the exhaust gas during the detailed emission testing. The unit was calibrated during the test period using zero gas and SO_2 in air standard gas.

Oxides of Nitrogen

A Thermo-Electron Model 44, Chemiluminescent NO/NO_x Analyser was used for the measurement of nitrogen oxides. Total oxides of nitrogen (NO_x) and nitric oxide (NO) were measured alternately, the difference between the two being assumed to be nitrogen dioxide (NO_2). Research grade oxygen was supplied to the instrument's ozone generator. Calibration was performed using "zero air", NO and N_2 span gases.

Flue Gas Particulate Collection

A Joy Emission Parameter Analyser was used for collection of particles carried out in the flue gas.

Combustibles in the Ash Collected in the Furnace

Ash removed from the burner was collected in the ash hopper. Subsequently an ash sample was removed from the hopper and analyzed for combustibles using an adiabatic bomb calorimeter.

5.3 Measurement of Flue Gas Particulate Loading

Particulate sampling of the exhaust gas was performed in general accordance with the Ontario Source Testing Code using a Joy Manufacturing Emission Parameter Analyser Method 5 Source Testing Train as shown in Figure 4.

The following procedure was used in performing the particulate tests. A sample of the stack gas is withdrawn isokinetically, via a 1.27 cm diameter gooseneck nozzle and a stainless steel lined 2 m long heated probe (to prevent condensation) to a heated oven. The oven, usually maintained at or above 121°C contains a filter holder and a glass fiber filter, (Reeve Angel 900 AH), to remove the particulate matter. Following filtration, the sample passes through a series of four impingers immersed in an ice bath. This permits the determination of stack gas moisture content and also protects downstream components from excess moisture. The first two impingers each contain 125 mL of water, the third is empty, and the fourth contains silica gel. The stack gas, now filtered and dried, is drawn through the umbilical line, up to 30 m in length, to the control module.

The control module consists of a leak-free pump of capacity 0.03 m^3/min free air, with by-pass valve to withdraw the sample, a dry gas meter to measure the volume of gas samples, and a temperature monitoring system to measure temperatures in the stack, the probe, the oven, the impingers and at the gas meter. The controls for the probe and oven heaters are also incorporated in the control unit.

Isokinetic sampling is maintained by relating the sampling rate, shown by an orifice meter, to the stack gas velocity. This mathematical relationship is established by a set of preliminary tests in which stack gas moisture, molecular weight and temperature are determined. Velocity pressure is measured continuously with an 's' type pitot tube (Coefficient 0.80) attached to the sampling probe.

During each test the stack or duct is usually sampled at a number of points, on two or more traverses (two, 90^o apart, for a circular cross-section). In this way, a representative sample may be obtained. Usually sampling proceeds for a minumum of five minutes at each point, and, depending on the size of the stack and the sampling location, a test may last anywhere from 60 minutes to several hours.

Due to the small diameter stack only one sample point was used in the test program. That point was located slightly off the centre of the stack area. Isokinetic sampling was maintained for one hour.

At the end of each test the sampling train was disassembled and cleaned.

The probe and nozzle were rinsed with acetone.

The weight of solids in the probe rinse samples was obtained by filtration. An aliquot of each probe rinse filtrate was evaporated to dryness to determine the soluble fraction of particulates. Similarly, aliquots of each impinger solution were evaporated to dryness to determine the particulate weight gain. Aliquots of distilled water were also evaporated to dryness to determine blank values.

The total weight of particulate for emission rate calculations was obtained by adding together the weight of particulate on the filter, and the probe rinse soluble and insoluble particulate weights.

6.0 TEST PROCEDURE

6.1 General Burner Operation

Pre-Ignition

The four samples of wood pellets used in the test program were evaluated for moisture content, calorific value and ash content on the basis of composite sub-samples drawn from the sample.

Ignition

In order to establish flue draft, the test furnace was preheated with furnace (No. 2) fuel oil for a period of approximately an hour.

After preheating, the furnace was loaded with 4.5 kg. (10 lbs.) of biomass fuel pellets using a 0.15 m diameter, 0.75 m long chute. The first loads of the three load cycle for each of the four biomass pellet fuels evaluated were ignited with a gas burner from a domestic water heater. The second 4.5 kg. loads were also ignited with the gas burner, except for the pellets of fuel "E" which were ignited by glowing charcoal of the first load. The third loads of biomass fuel pellets were ignited by glowing beds of charcoal. The second and third loads of fuel pellets were added to the furnace after the flue gas temperature dropped down to approximately 140°C. The third burn cycle was terminated after the flue gas temperature dropped to 115°C as recommended in the CSA draft Standard for testing of solid fuel fired appliances [2]. The ash and coals in the furnace were collected, weighed and analyzed for heating value.

Combustion

The test program encompassed three combustion cycles of 4.5 kg. charges of biomass fuel pellets for each fuel type. Each test started with preheating the furnace with No. 2 fuel oil for a period of an hour. After preheating, the furnace was loaded with 4.5 kg. of wood pellets. Partial test data, including temperatures CO, O_2, CO_2 and fuel use rate were recorded during the first cycle from the time of ignition. An initial attempt to collect full emission test data during the first cycle had to be aborted, due to excessive plugging of the gas sampling and conditioning train of the full computerized emission testing system. Full test data including flue gas analysis was recorded during the remaining two cycles for each fuel. During the first cycle the furnace controls were set to maintain firing rate at approximately 100 MJ/h to ensure complete combustion of pellets in 1.5 - 2 hours. The controls were maintained at the setting throughout the entire test program. The draft was maintained at .035" H_2O throughout the testing. An additional 4.5 kg. charge of pellets was loaded into the furnace just before the end of the first burn cycle. The above procedure was repeated for the third 4.5 kg. charge. During the test, all temperatures and output from flue gas analysers and load cell (furnace and charge weights) were recorded on the central acquisition system, as well as air flow rate to the furnace heat exchanger. At the end, the residue was quenched with dry ice and were removed from the furnace and weighed.

Data Collected

During each test the following information was collected:

- Charge weight
- Ash and coals weight
- Percent combustibles in the ash
- Combustion efficiency
- Time required for combustion of two loads
- Flue analyses for CO_2, CO and O_2, NO_x, SO_2 and THC
- Flue temperature
- Cold air temperature, temperature rise and flow rate
- Rate of fuel consumption
- Experienced problems
- Furnace efficiency with No. 2 fuel oil and approximate efficiency with Energex pellets

Calibration runs, using No. 2 fuel oil, were made at the beginning and end of the program in order to check the results obtained on the wood fuel. All biomass fuel tests were carried out at approximately 100 MJ/h firing rate.

7.0 RESULTS

7.1 Preignition

The characteristics of the four test fuels including density, moisture, heating value and ash are shown in Table 1. Computed ash contents of fuels from the test data are compared with the laboratory analysis in Table 1. Comprehensive physical and chemical data for Energex are given in Table 2.

The main points of the fuel characteristics are as follows:

1. All four types of biomass fuel pellets used in the test program were 6 mm in diameter and an average 20 mm long.

2. Fuel "C" (100% Pine Jack) had the highest specific gravity of 1.33 with respect to water, followed by fuel "D" (98% Pine Jack + 2% Polyethylene) at 1.3. Fuel "B" (Energex) had the lowest density of 1.06.

3. Heating values of fuels listed in descending order are fuel "E" at 20.69 MJ/kg, followed by fuel "D" at 19.78 MJ/kg, fuel "C" at 19.65 MJ/kg and fuel "B" at 17.0 MJ/kg.

4. Energex (fuel "B") had the highest ash content of nominally 5% compared to nominally 0.2% for the jack pine based fuels.

7.2 Ignition

The times required for igniting of the first and second fuel charges using the auxiliary gas burner are shown in Table 3. The easiest fuel to ignite initially was the jack pine + 2% polyethylene. This fuel required 0.7 min. of auxiliary ignition source. The second easiest was the 100% jack pine requiring 1.5 min. and the next was Energex requiring 2.3 min. The most difficult to ignite was the 95% jack pine + 5% polyethylene. It required 2.9 min. of auxiliary ignition source. The last fuel, while the most difficult to ignite during the first burn cycle, became the easiest to ignite in the second cycle, as it required no auxiliary ignition source at all.

The results of comparative combustion tests of commercial and improved biomass fuel pellets in the 150 MJ/h wood/fuel/ oil furnace are summarized in Table 4. These test results are the averages of the last two of the three 4.5 kg. load cycles that were used for each fuel type. The combustion, emission and heat transfer parameters collected every 2.5 minutes and averaged every 5 minutes and collected every five minutes during the last two burn cycles in the test furnace are summarized in Tables 7 to 18.

The overall combustion test data for each of the four fuels are broken down into the following five groups of parameters:

1. Burn Rate
2. Combustion Parameters (O_2, CO_2, Flue Temp.)
3. Emissions A (SO_2, NO_x)
4. Emissions B (CO, THC)
5. Heat Transfer (Energy Output and an Estimate of Energy Input)

For each of the four biomass fuels these five groups of parameters are given in Figures 5 to 21.

Table 5 gives the initial and final weights for the fuel charge during the test. Table 6 depicts data on the estimated furnace efficiency for the reference "Energex" fuel, the base fuel without polyethylene and with polyethylene for conditions of the last 4.5 kg. cycle, last two 4.5 kg. cycles and the entire three 4.5 kg. cycle test program. These furnace efficiencies were not corrected for carbon in the ash.

7.3 Combustion

A brief summary of the combustion program test results is given in Table 4.

Referring to Table 4 - the combustion of the pine fuel pellets with 2% and 5% polyethylene compare favourably with that of the reference Energex fuel. The reference fuel had higher CO, THC, and NO_x than the other test fuels. The three types of pine fuel pellets that were tested had higher gas particulate loadings than the reference fuel.

However the Energex pellets had a much higher level of total hydrocarbons in the flue gases.

The calculations for determining combustion efficiency are given in Appendix 2. Fuel "B" (Energex) had the lowest combustion efficiency of 66%, followed by fuel "C" at 85%, fuel "D" at 89.7%, and fuel "D" at 91.1%.

Furnace efficiency based on the average test data of the last two of the three cycle test program indicated highest efficiency of nominally 53% for Energex and nominally 50% for the 3 types of pine pellets. The higher efficiency for Energex is attributed to that fuel's lower burning rate.

7.4 Burn Rate

Figures 5 and 6 show the total fuel consumed vs. time for the four test fuels. The slope of the curves indicate the burning rate of the fuels.

7.5 Energy Input and Output

The estimated energy input and the measured energy output test data and the test data curves plotted against time for the reference Energex fuel and the three jack pine based fuels with and without polyethylene are given in Tables 9, 12, 15 and 18 and Figures 19 to 22.

7.6 Combustion Intensity - CO_2 in the Flue Gas

Figures 7, 8, 9, and 10 provide combustion parameters for the reference fuel ("B") and the three test fuels "C", "D", "E". The combustion parameters include flue gas temperature, carbon dioxide and oxygen. High flue gas temperature as a rule indicates high combustion intensity. High concentration of carbon dioxide indicates high combustion intensity and low excess air. Analysis of the burn cycle of the third 4.5 kg. load of the reference and the three test fuels indicates the following:

Fuel "C" (100% jack pine) achieved the highest concentration of CO_2 of 13.5% (48% excess air) in the flue gas after approximately 10 minutes into the third cycle and had the shortest burn cycle of approximately 45 minutes.

The highest concentration of CO_2 for fuel "D" (98% jack pine + 2% polyethylene) of 11.4% (76% excess air) in the flue gas was achieved after approximately 20 minutes into the third cycle. Its burn cycle lasted for approximately 70 minutes.

The highest concentration of CO_2 for fuel "E" (95% jack pine + 5% polyethylene) of 9.6% (101% excess air) was achieved at approximately 5 minutes into the cycle. The burn cycle lasted approximately 40 minutes.

The highest concentration of CO_2 reference fuel "B" (Energex) of 7.4% (168% excess air) was achieved at approximately 20 minutes into the third burn cycle. This fuel had a 60 minute burn cycle.

7.7 Emissions

Sulphur dioxide (SO_2) and nitrogen oxides (NO_x) emissions of the reference Energex fuel and the three jack pine fuels with and without polyethylene are given in Figures 11 to 14 and indicate the following:

Highest concentrations of nitrogen oxides and sulphur dioxide in the flue gas are measured during times of highest combustion intensity. These emissions drop with drop in the combustion intensity for all fuels except for the reference Energex fuel. For this fuel sulphur dioxide emissions increase, particularly during the last burn cycle and also increase with time. The maximum NO_x concentration measured and the average are about the same for the last two burn cycles. Sulphur dioxide concentrations are highest for the last burn cycle except for the fuel "E" containing 95% pine/5% polyethylene. For this fuel both average and the maximum SO_2 in the flue gas during the last two burn cycles were approximately the same.

Carbon monoxide (CO) and hydrocarbons (THC) emissions of the base Energex fuel and the three jack pine fuels with and without polyethylene are given in Figures 15 to 18 and indicate the following:

As expected highest concentrations of CO and THC in the flue gases were measured at the beginning of the new burn cycle.

At the beginning of the third cycle maximum concentrations of CO of approximately 4000 PPM were measured for all fuels except fuel "E" containing 95% pine (jack) + 5% polyethylene. For this fuel maximum concentration of CO of slightly over 3000 PPM was measured at the end of the first and the beginning of the second cycle. At the beginning of the third cycle the maximum concentrations of CO of nominally 3300 PPM were measured for this fuel "E" with the first concentration peak slightly higher. At the beginning of the third cycle all test fuels except Energex had two peaks of maximum CO concentration with second peak showing higher CO concentrations. Maximum concentrations of THC in the flue gas were measured at the same cycle time as those of CO.

100% jack pine fuel "C" had the lowest peak THC concentration of nominally 700 PPM, followed by Energex "B" of nominally 2000 PPM, fuel "D" containing 98% jack pine + 2% polyethylene, and fuel "E" containing 95% jack pine + 5% polyethylene fuels had nominally the same THC concentrations in the flue gas at approximately 2600 PPM.

7.8 General Observations

a) Energex fuel demonstrated considerably higher rate of dirt (tar and/or creosote) in the flue gas as indicated by frequent need for cleaning the flue gas sampling train, and the high total hyrdocarbon content of the flue gases.

b) When refuelling with the 2% and 5% polyethylene fuels, cindering coals had a blueish red glow compared to the previous fuels which had a reddish glow.

c) Analysis of coals of Energex and pine fuels collected at the end of the 13.5 kg test program for ash (given in Table 5) indicated nominally 5% and 0.2% ash content respectively. This compared to nominally 4% and 0.3% ash content of Energex and pine fuels obtained from laboratory analysis of fuel samples.

8.0 CONCLUSIONS

The detailed comparative combustion tests that were carried out to establish trends in the overall fuel performance versus fuel type indicated that the developed fuel pellets had combustion characteristics that are equal or superior to those of the commercially available Energex fuel pellets.

9.0 RECOMMENDATIONS

It is recommended that combustion tests of pellets be carried out using an industrial type biomass burner.

It is also recommended that methods for continuous monitoring of fuel quality be investigated. This is critical to effective burner operation and control.

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Energy Systems Centre
Engineering Sciences Division

D. Giannini
Energy Systems Centre
Engineering Sciences Division

REFERENCES

1. International Bio-Energy Director and Handbook 1984 (P.X1)

2. CSA Draft Standard B-415 - "Performance Testing of Solid Fuel Burning Appliances"

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1) Matolczy, G.A., Hansmann, A., "Development of a Moisture Resistant Densified Solid Fuel from Forest Biomass", Report P-4590/G-7, 13 p., April 18, 1986.

2) Tyrcz, E.T., "Fluidized Bed Combustion" ORF Internal Report

3) Tyrcz, E.T., Shaw, M., Giannini, D., "Test and Development Facility for Solid Fuel Combustion Systems", ORF Internal Report.

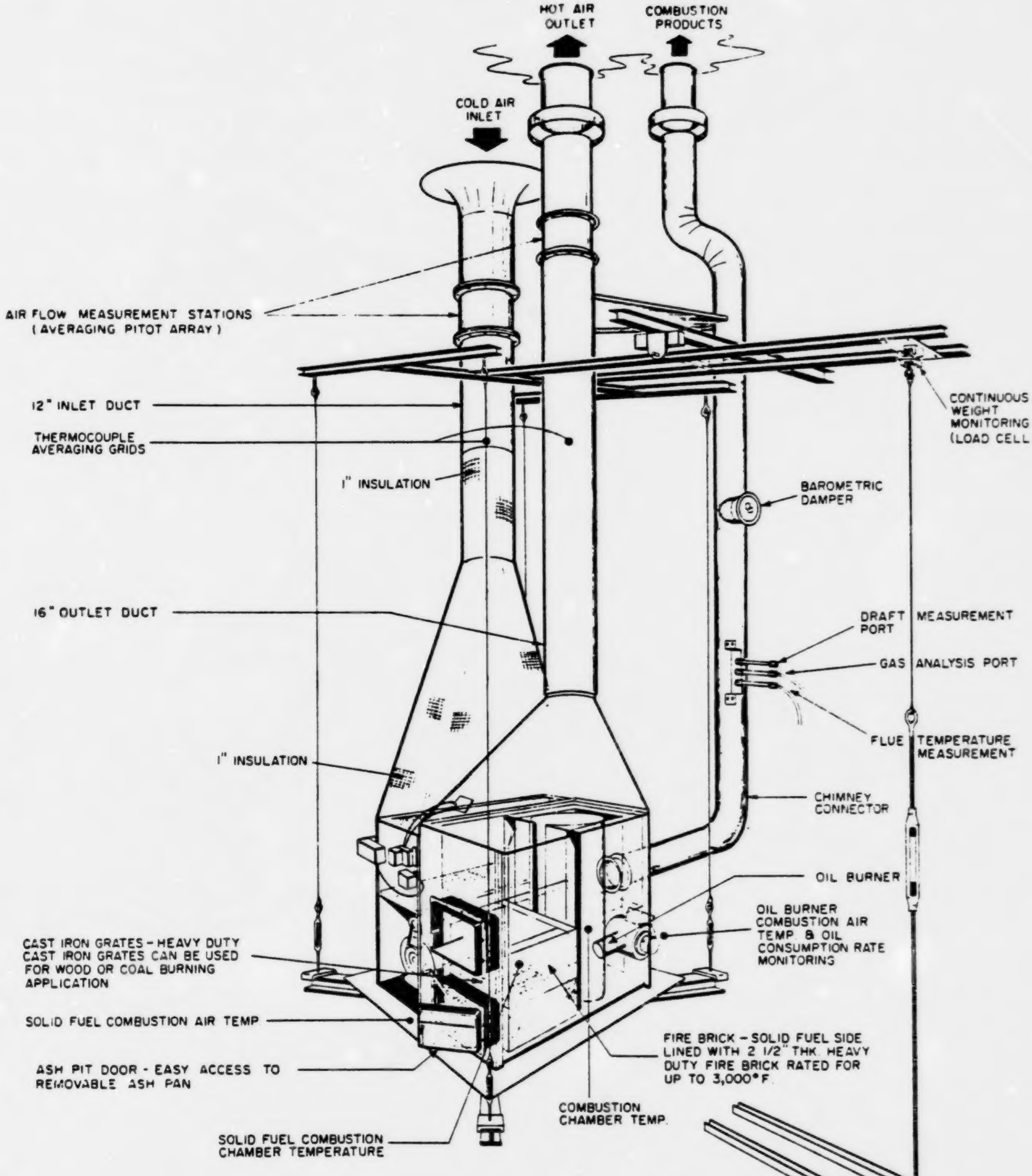

HOT AIR OUTLET
COMBUSTION PRODUCTS
COLD AIR INLET
AIR FLOW MEASUREMENT STATIONS (AVERAGING PITOT ARRAY)
12" INLET DUCT
THERMOCOUPLE AVERAGING GRIDS
CONTINUOUS WEIGHT MONITORING (LOAD CELL)
1" INSULATION
BAROMETRIC DAMPER
16" OUTLET DUCT
DRAFT MEASUREMENT PORT
GAS ANALYSIS PORT
FLUE TEMPERATURE MEASUREMENT
1" INSULATION
CHIMNEY CONNECTOR
OIL BURNER
OIL BURNER COMBUSTION AIR TEMP. & OIL CONSUMPTION RATE MONITORING
CAST IRON GRATES - HEAVY DUTY CAST IRON GRATES CAN BE USED FOR WOOD OR COAL BURNING APPLICATION
SOLID FUEL COMBUSTION AIR TEMP
FIRE BRICK - SOLID FUEL SIDE LINED WITH 2 1/2" THK. HEAVY DUTY FIRE BRICK RATED FOR UP TO 3,000°F.
ASH PIT DOOR - EASY ACCESS TO REMOVABLE ASH PAN
COMBUSTION CHAMBER TEMP.
SOLID FUEL COMBUSTION CHAMBER TEMPERATURE

FIGURE 1: TEST and DEVELOPMENT FACILITIES for SOLID FUEL COMBUSTION SYSTEMS

ONTARIO**RESEARCH**
FOUNDATION

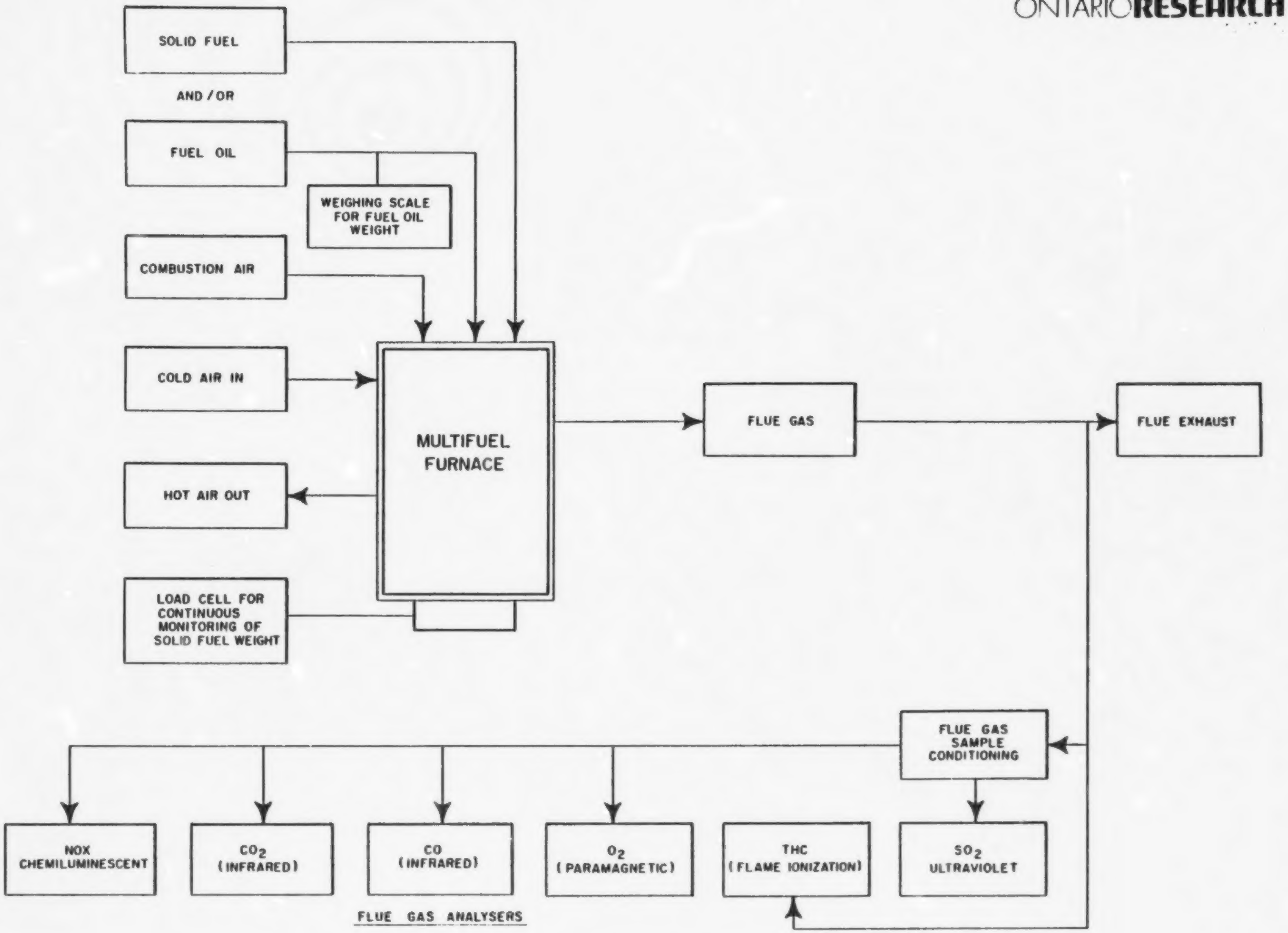

SOLID FUEL
AND / OR
FUEL OIL
WEIGHING SCALE FOR FUEL OIL WEIGHT
COMBUSTION AIR
COLD AIR IN
HOT AIR OUT
LOAD CELL FOR CONTINUOUS MONITORING OF SOLID FUEL WEIGHT
MULTIFUEL FURNACE
FLUE GAS
FLUE EXHAUST
FLUE GAS SAMPLE CONDITIONING
NOX CHEMILUMINESCENT
CO_2 (INFRARED)
CO (INFRARED)
O_2 (PARAMAGNETIC)
THC (FLAME IONIZATION)
SO_2 ULTRAVIOLET
FLUE GAS ANALYSERS

FIGURE 2: BLOCK DIAGRAM

TEST and DEVELOPMENT FACILITIES for SOLID FUEL COMBUSTION SYSTEM

FIG. 3 MOBILE SOURCE MONITORING LABORATORY (M.S.M.L.)

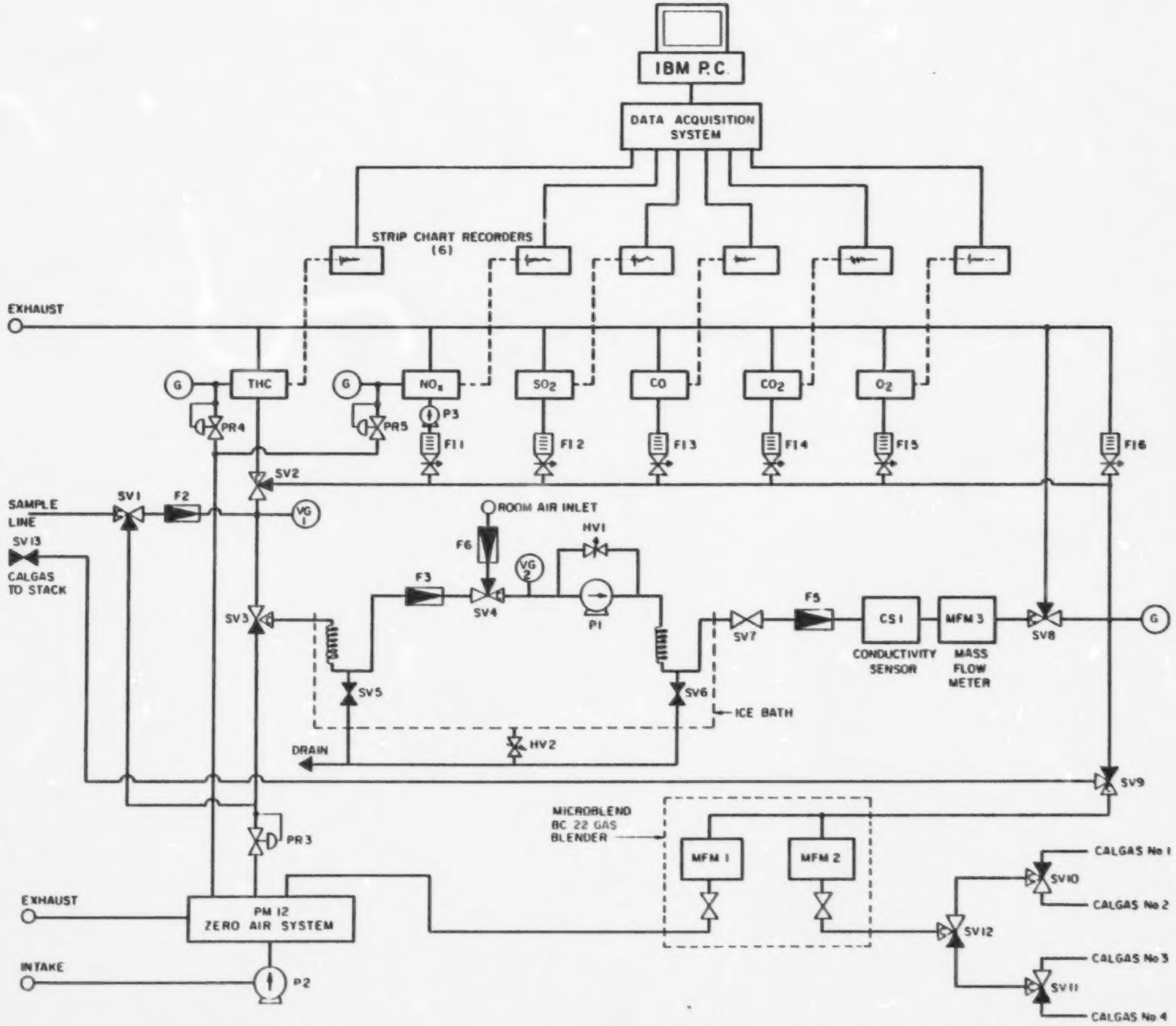
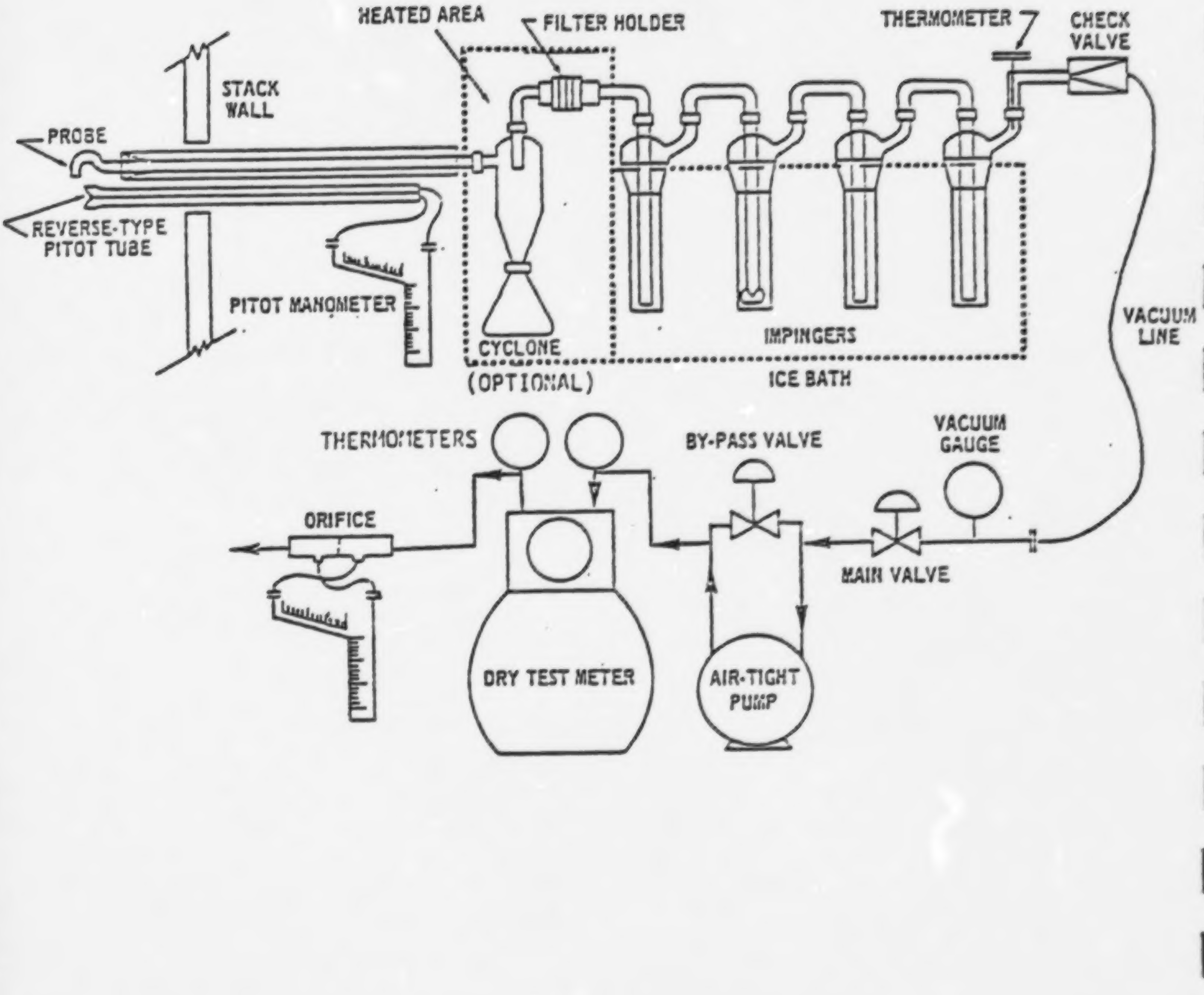

IBM P.C.
DATA ACQUISITION SYSTEM
STRIP CHART RECORDERS (6)
EXHAUST
G
THC
PR4
G
NO$_x$
PR5
P3
SO$_2$
CO
CO$_2$
O$_2$
FI1
FI2
FI3
FI4
FI5
FI6
SV2
SAMPLE LINE
SV1
F2
VG 1
SV13
CALGAS TO STACK
ROOM AIR INLET
HV1
F6
VG 2
F3
SV4
P1
SV3
SV5
SV6
ICE BATH
DRAIN
HV2
SV7
F5
CS1
CONDUCTIVITY SENSOR
MFM 3
MASS FLOW METER
SV8
G
SV9
MICROBLEND BC 22 GAS BLENDER
MFM 1
MFM 2
PR3
EXHAUST
PM 12 ZERO AIR SYSTEM
INTAKE
P2
SV12
SV10
SV11
CALGAS No 1
CALGAS No 2
CALGAS No 3
CALGAS No 4

FIGURE 4 - PARTICULATE SAMPLING TRAIN


HEATED AREA
FILTER HOLDER
THERMOMETER
CHECK VALVE
STACK WALL
PROBE
REVERSE-TYPE PITOT TUBE
PITOT MANOMETER
CYCLONE
(OPTIONAL)
IMPINGERS
ICE BATH
VACUUM LINE
THERMOMETERS
BY-PASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
DRY TEST METER
AIR-TIGHT PUMP

CUMULATIVE WEIGHT LOSS VS BURN TIME OF DENSIFIED WOOD PELLETS BURNING IN OLSEN DUAL FUEL FURNACE

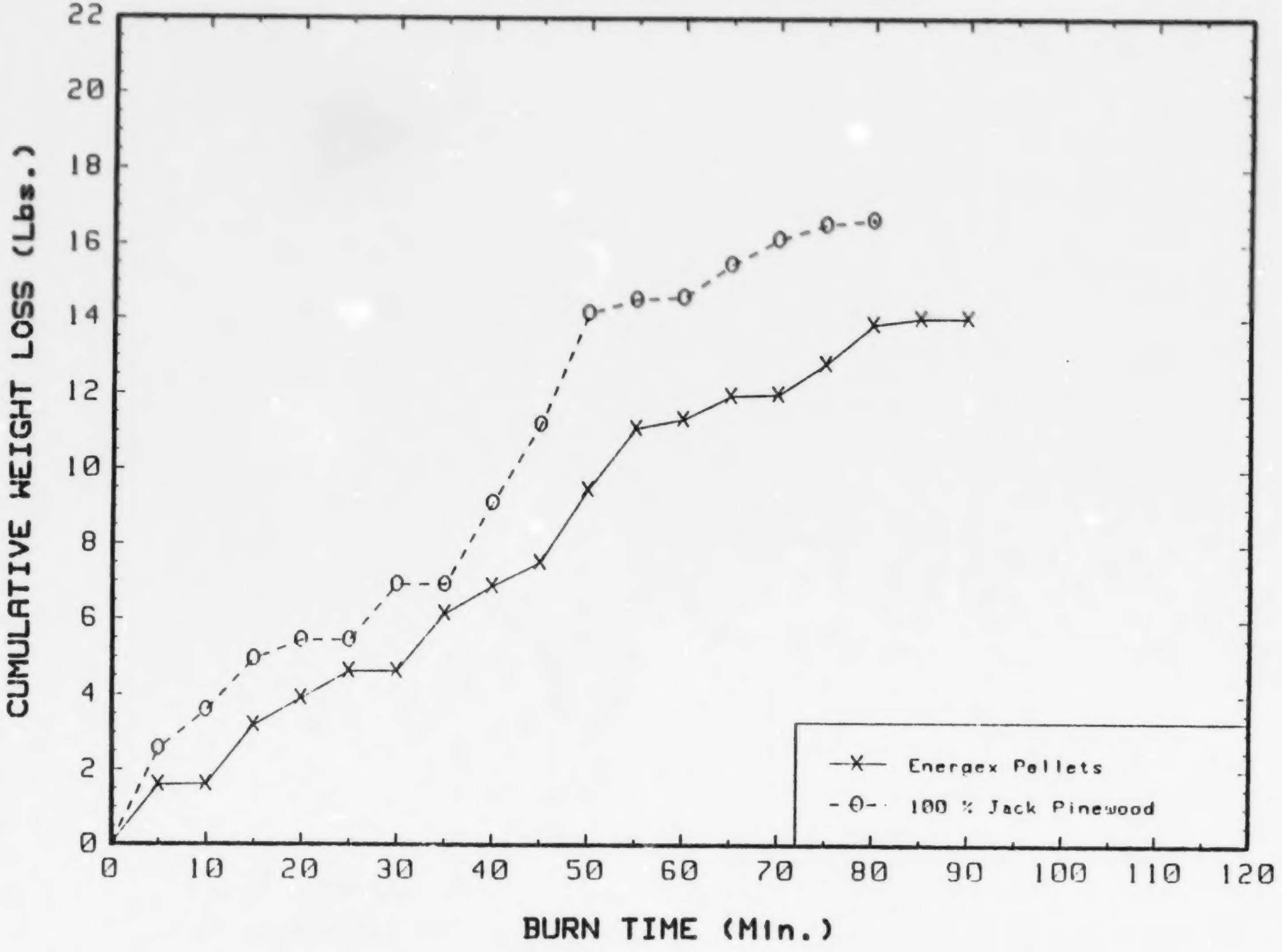


FIGURE 5

CUMULATIVE WEIGHT LOSS VS BURN TIME OF DENSIFIED WOOD PELLETS BURNING IN OLSEN DUAL FUEL FURNACE

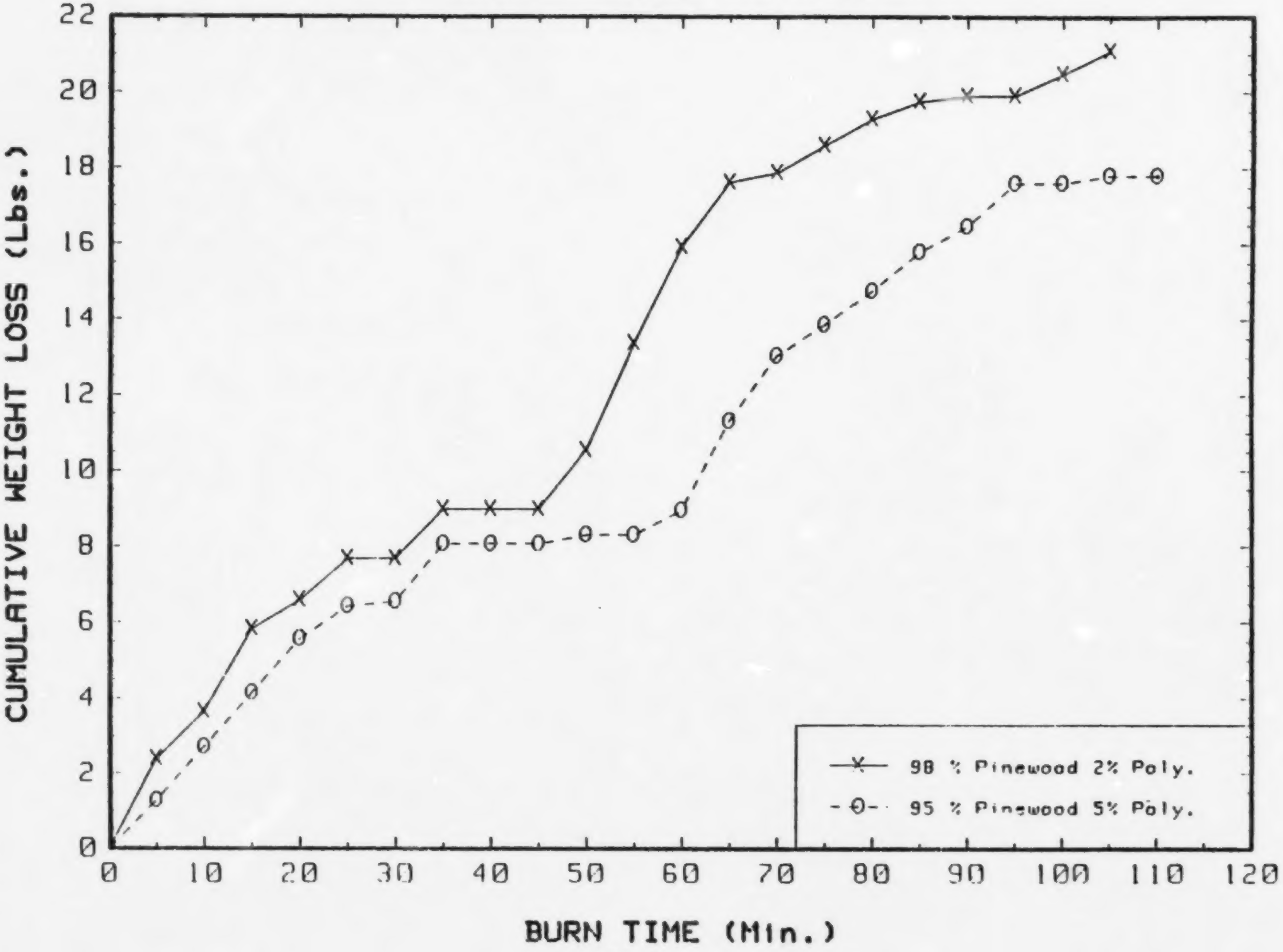


FIGURE 6

Combustion Characteristics Of Energex
Densified Wood Pellets

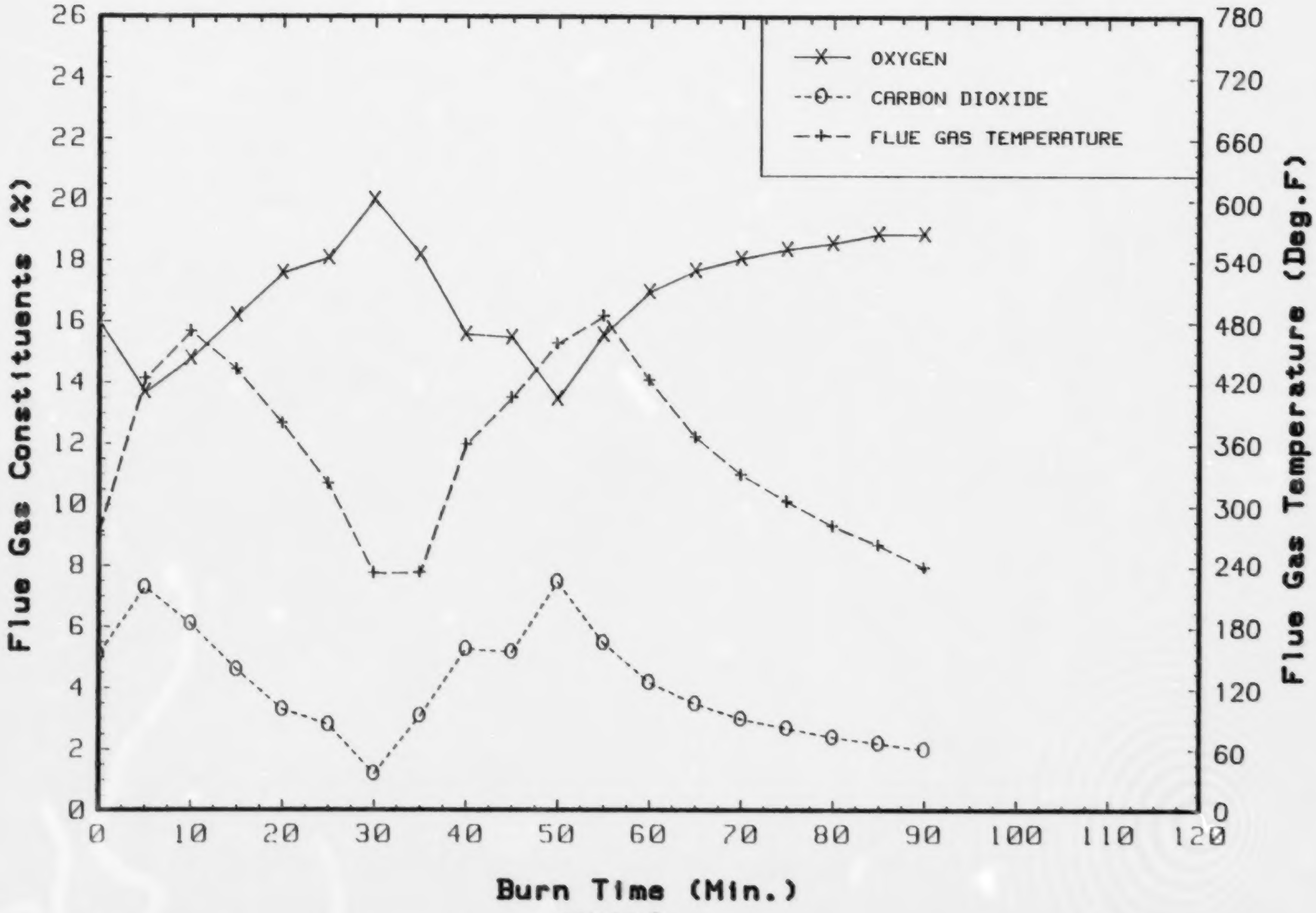


FIGURE 7

Combustion Characteristics Of 100% Pinewood Densified Wood Pellets

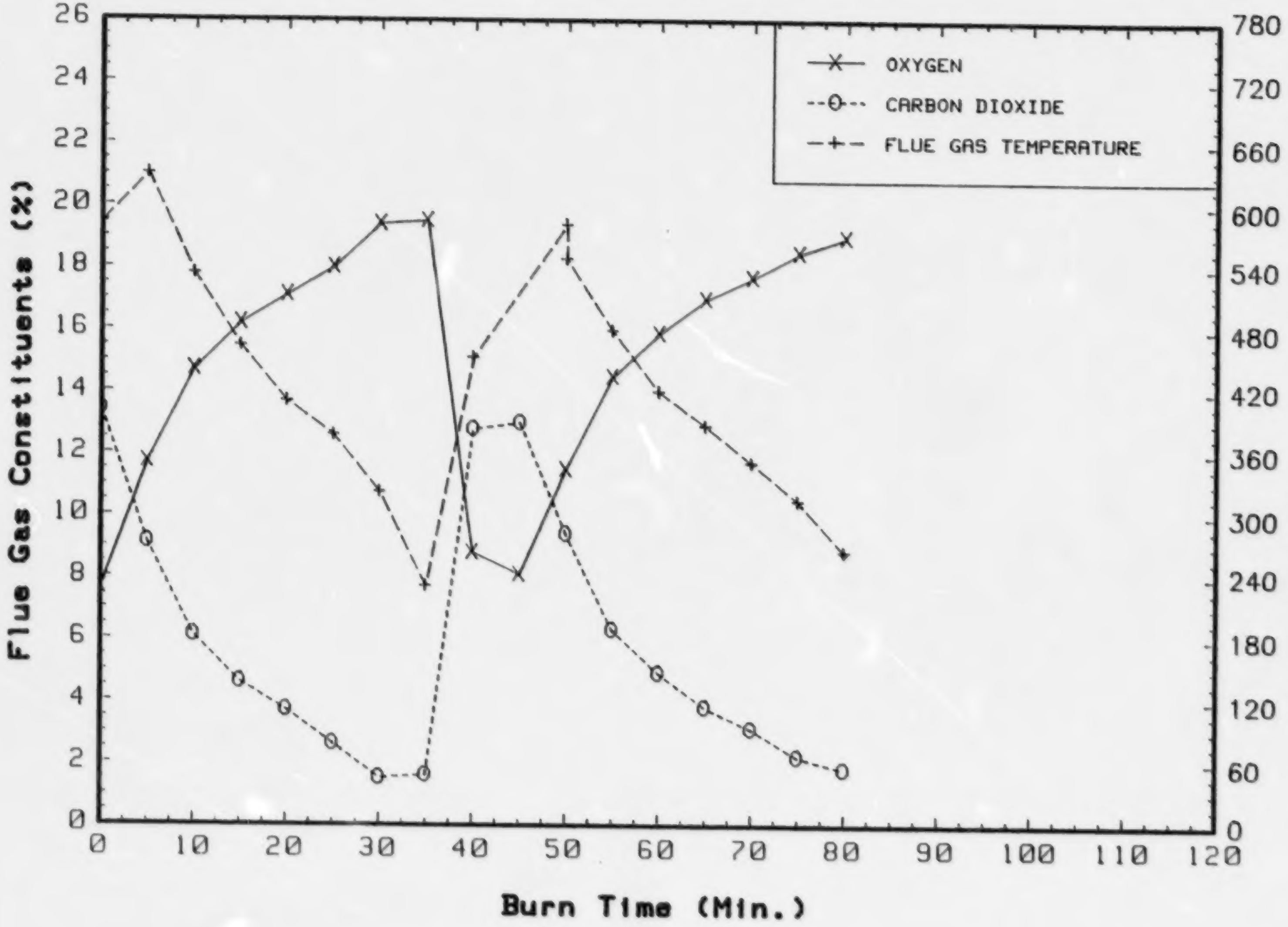


FIGURE 8

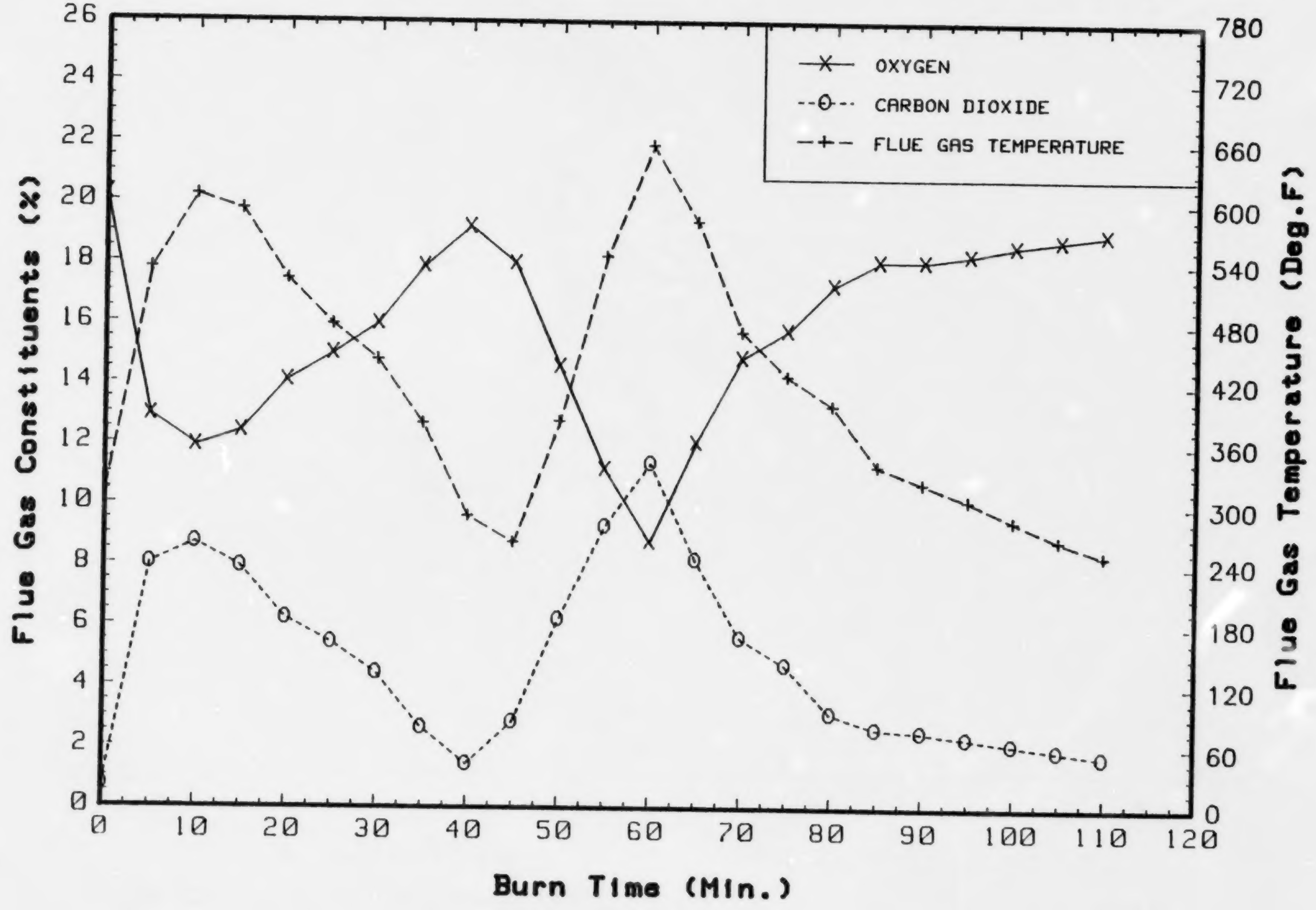

Combustion Characteristics Of 98% Pinewood
2% Polyethylene Densified Wood Pellets
OXYGEN
CARBON DIOXIDE
FLUE GAS TEMPERATURE
Flue Gas Constituents (%)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Flue Gas Temperature (Deg.F)
0
60
120
180
240
300
360
420
480
540
600
660
720
780
Burn Time (Min.)
0
10
20
30
40
50
60
70
80
90
100
110
120

FIGURE 9

Combustion Characteristics Of 95% Pinewood 5% Polyethylene Densified Wood Pellets

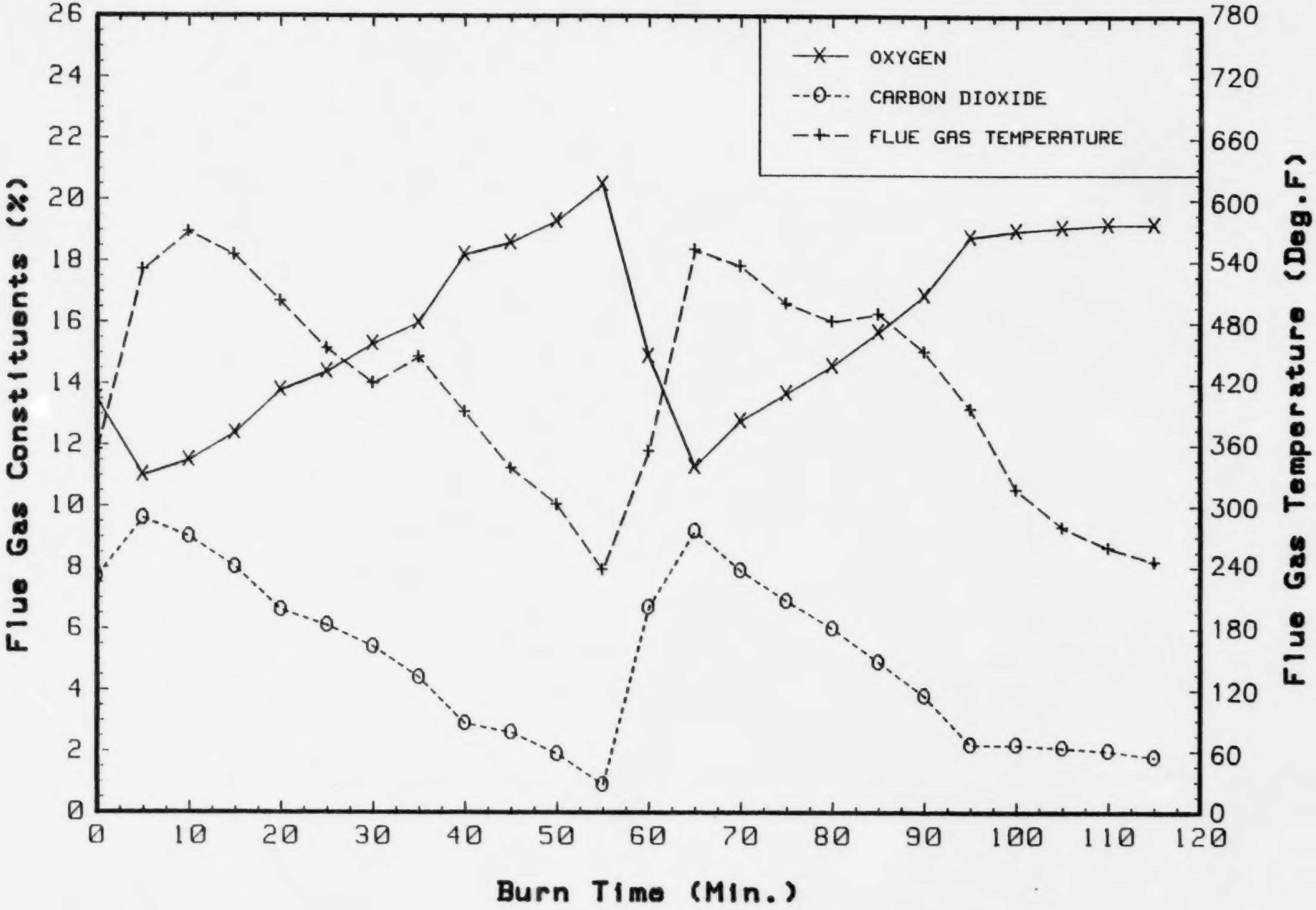


FIGURE 10

Combustion Characteristics Of Energex
Densified Wood Pellets

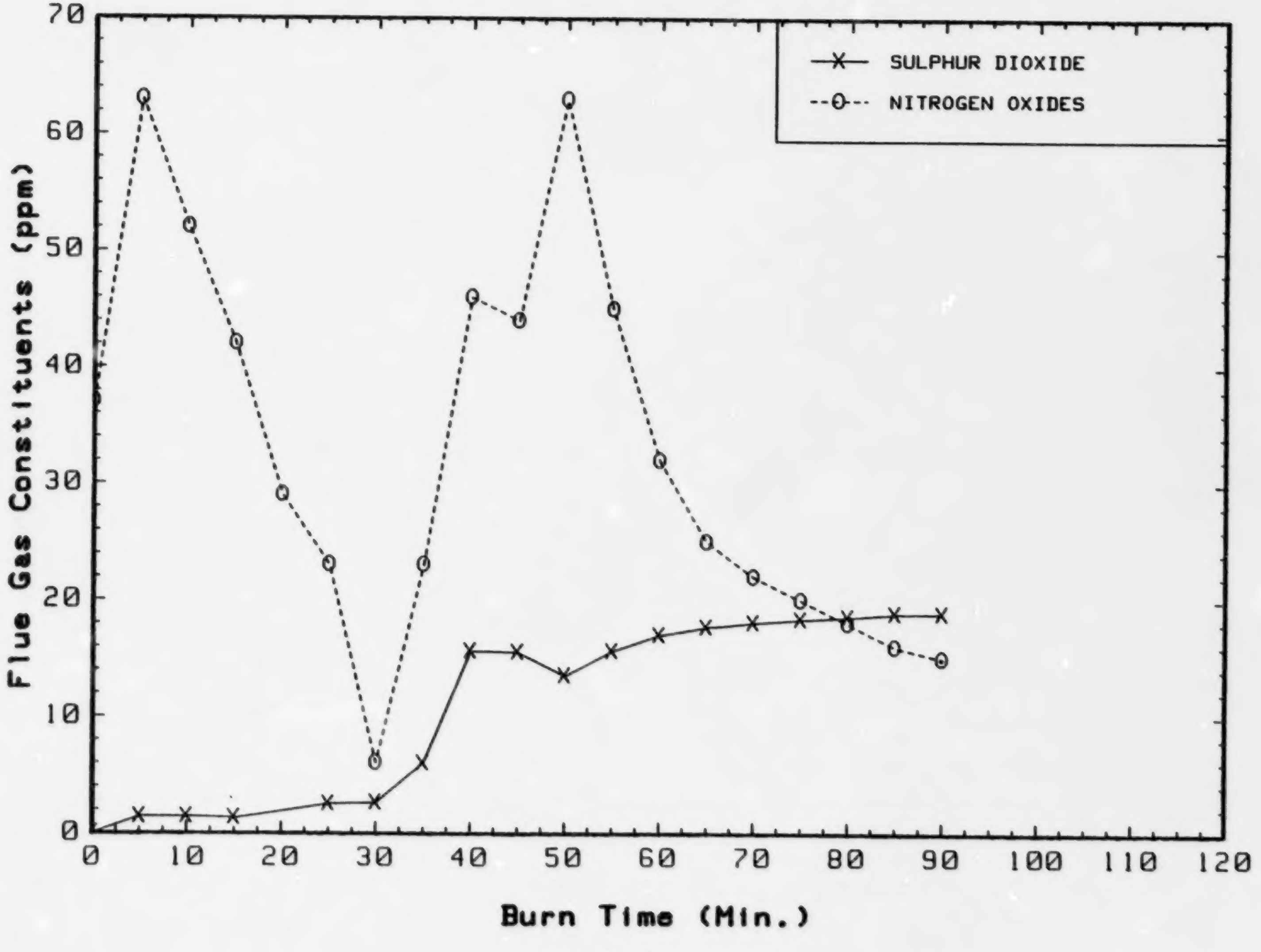
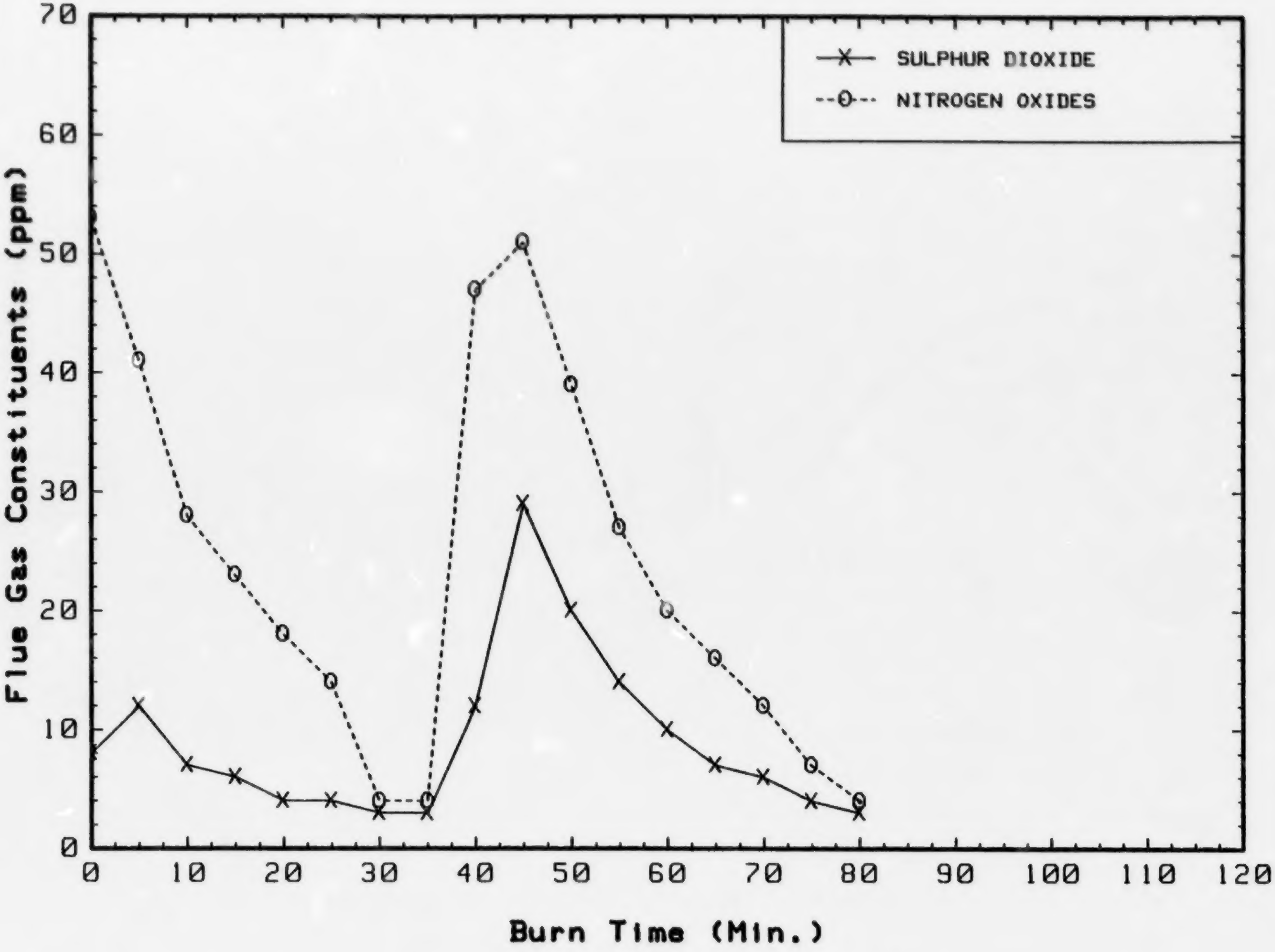


FIGURE 11



Combustion Characteristics Of 100% Pinewood Densified Wood Pellets

FIGURE 12

Combustion Characteristics Of 98% Pinewood
2% Polyethylene Densified Wood Pellets

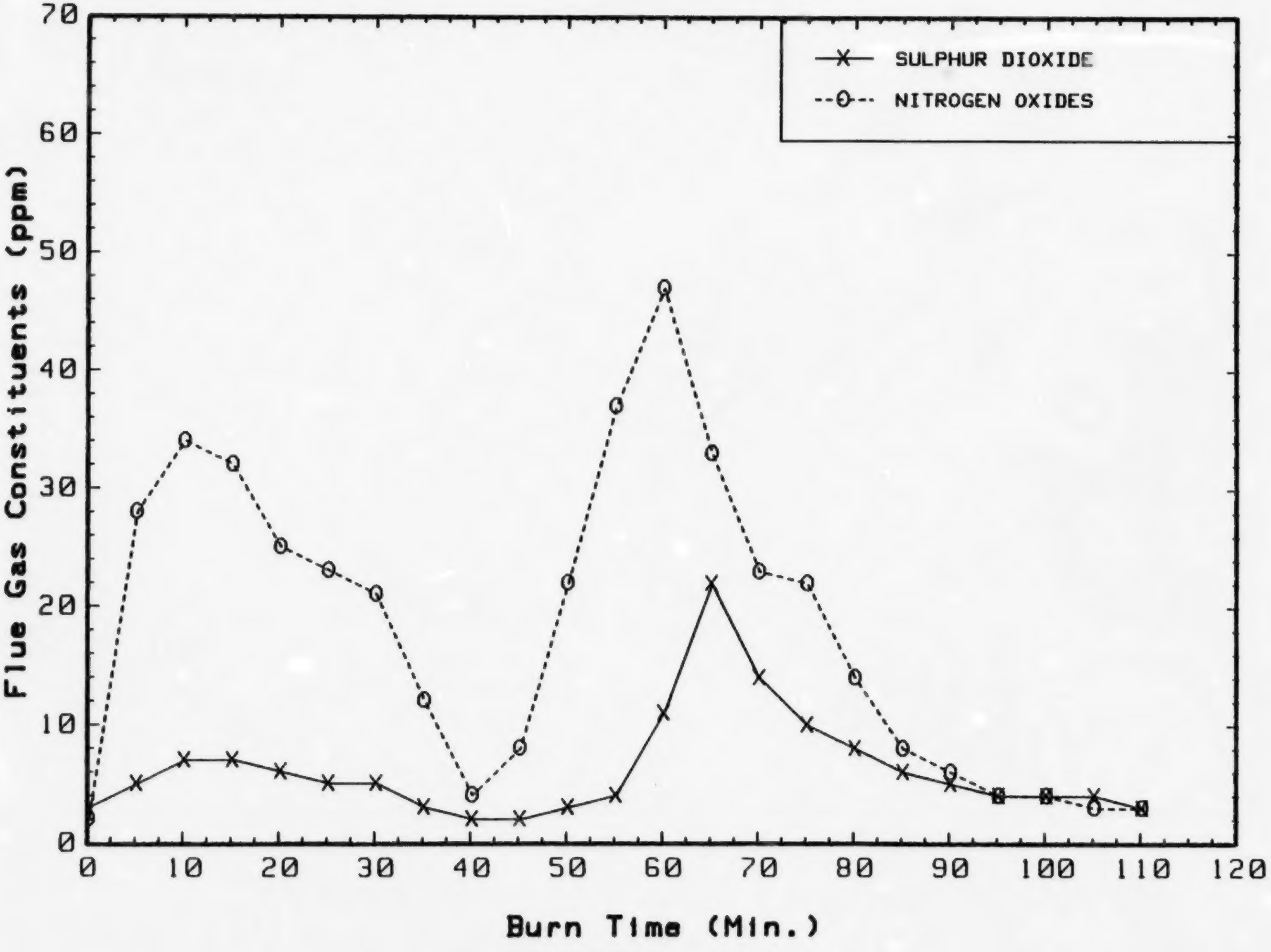


FIGURE 13

Combustion Characteristics Of 95% Pinewood 5% Polyethylene Densified Wood Pellets

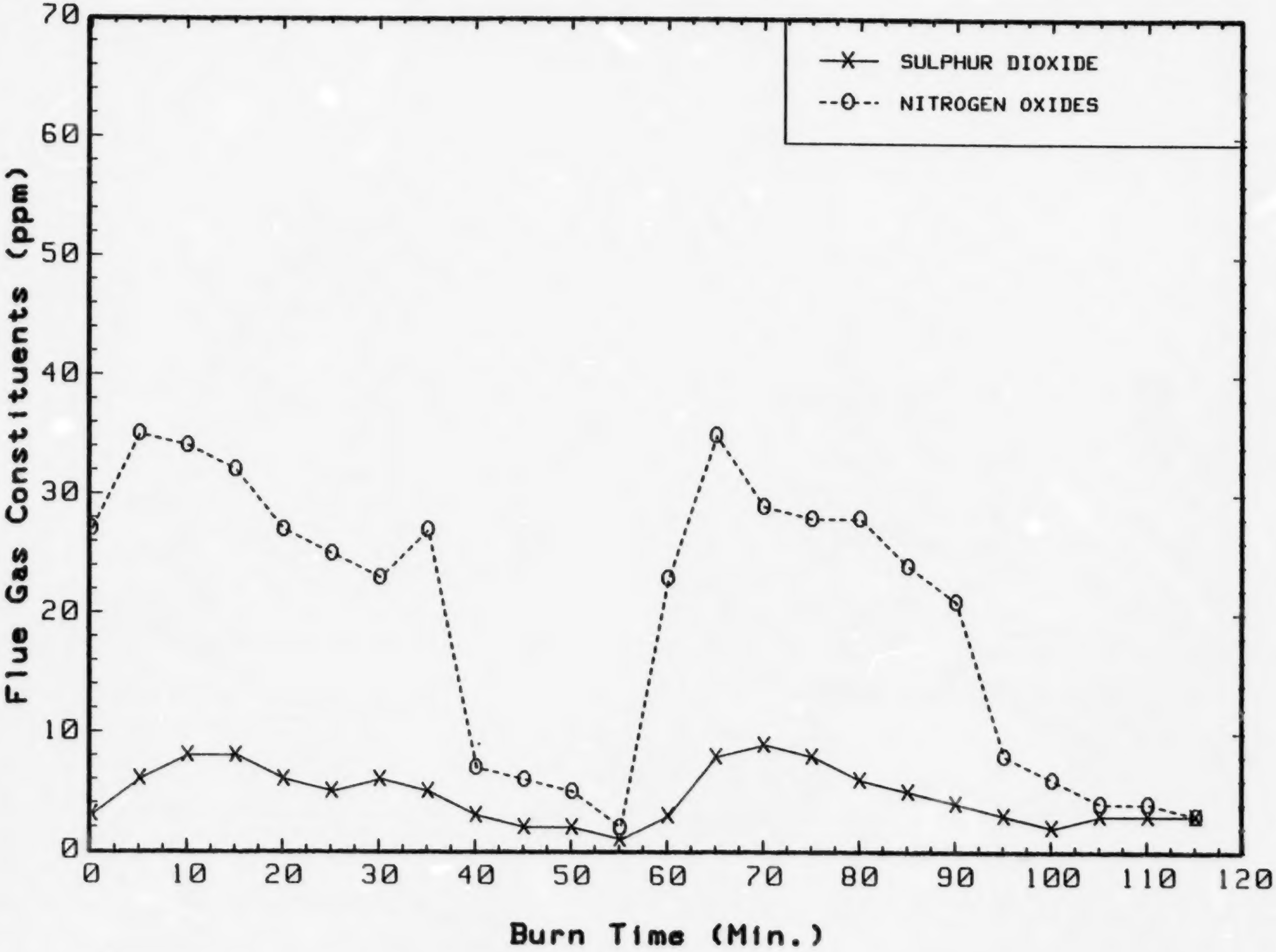


FIGURE 14

Combustion Characteristics Of Energex
Densified Wood Pellets

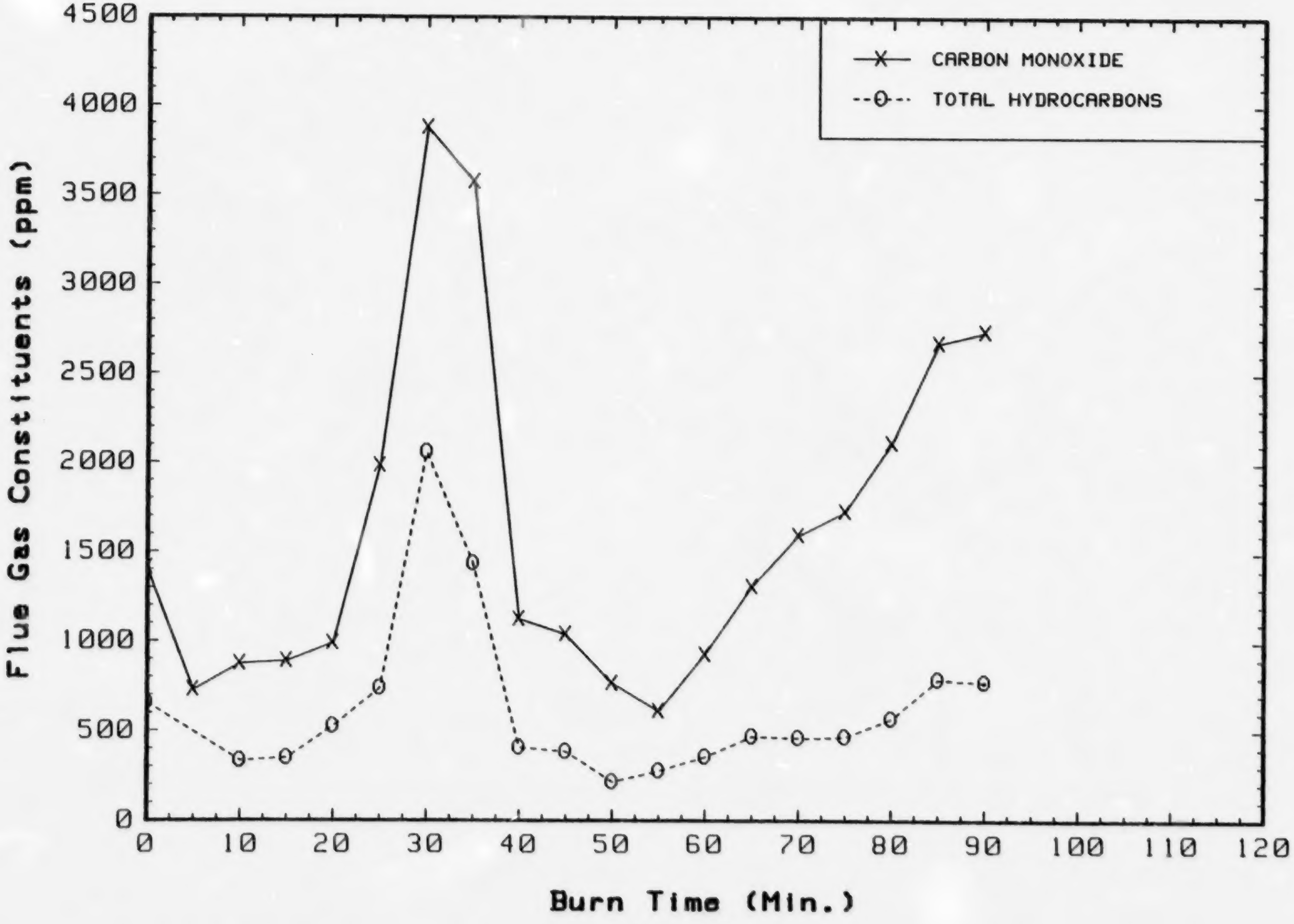


FIGURE 15

Combustion Characteristics Of 100% Pinewood
Densified Wood Pellets

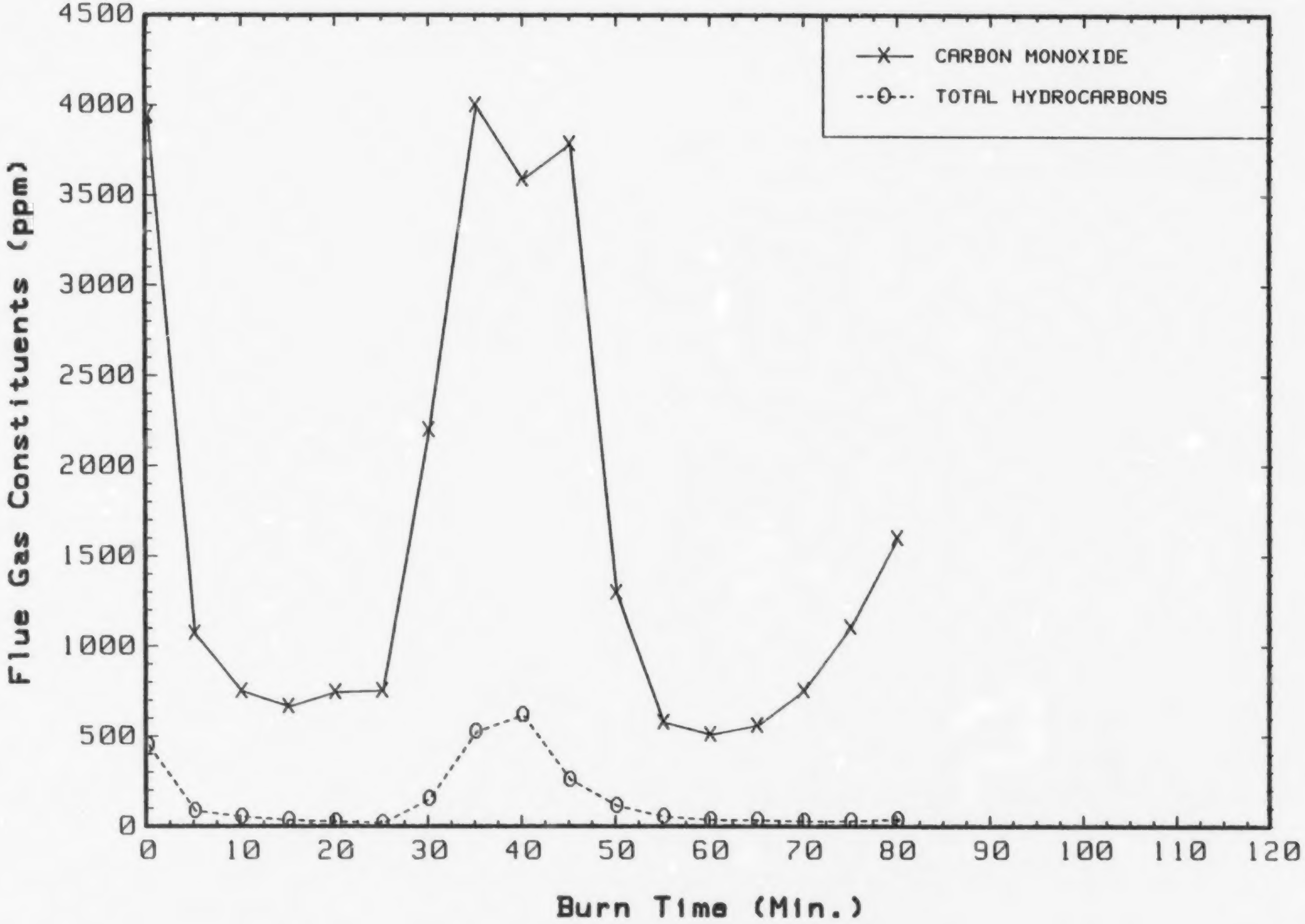
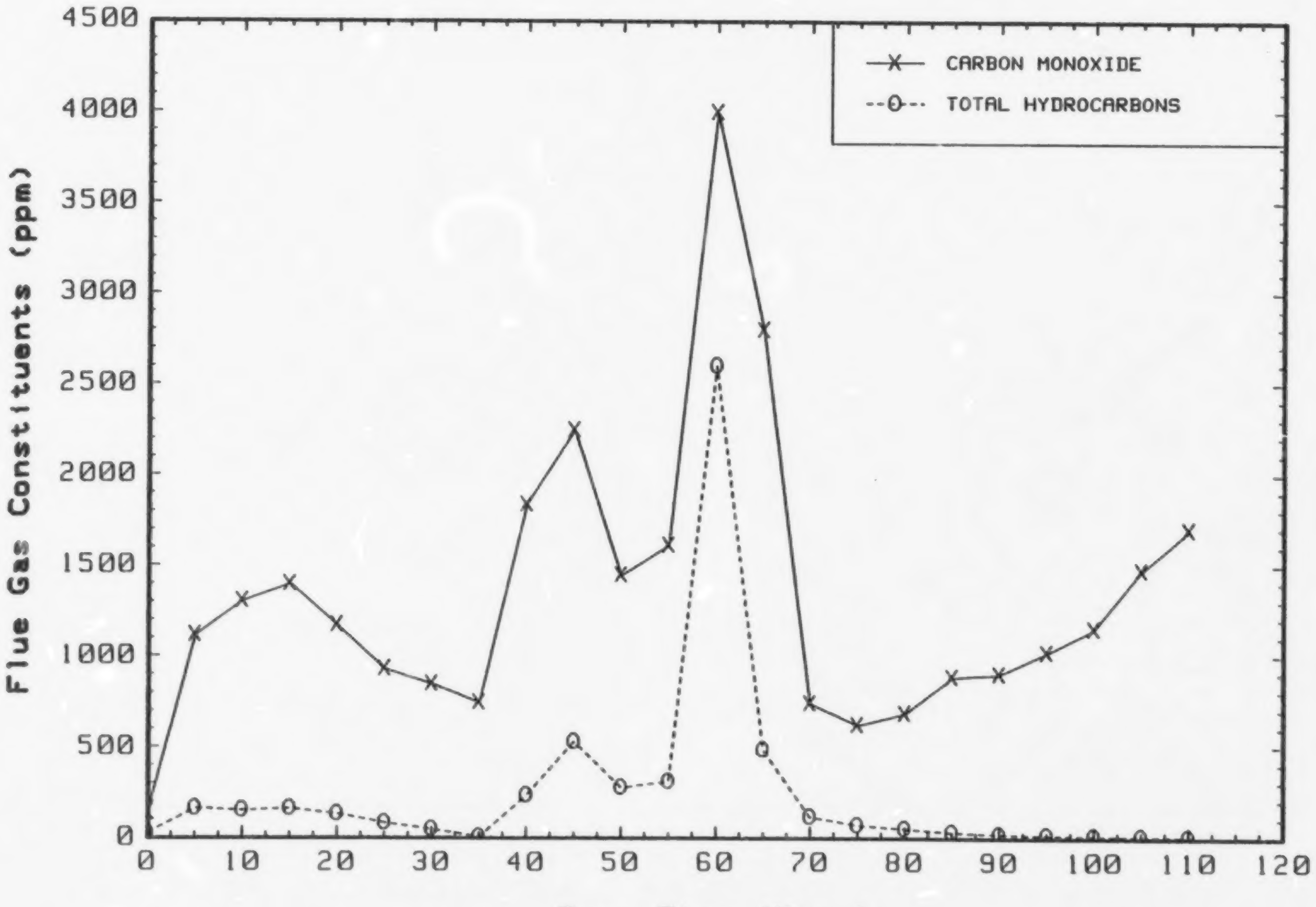


FIGURE 16



Combustion Characteristics Of 98% Pinewood
2% Polyethylene Densified Wood Pellets

FIGURE 17

Combustion Characteristics Of 95% Pinewood
5% Polyethylene Densified Wood Pellets

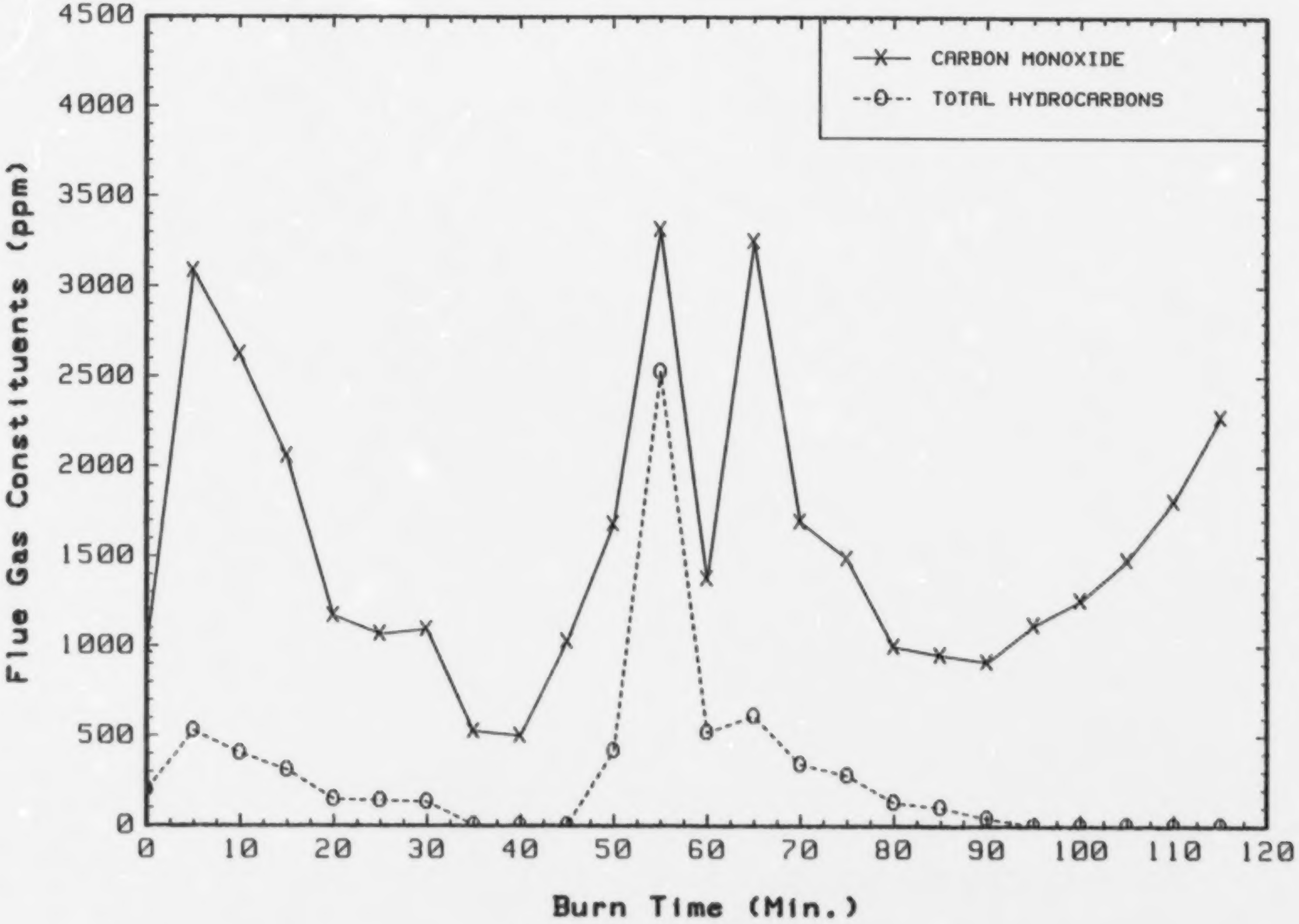


FIGURE 18

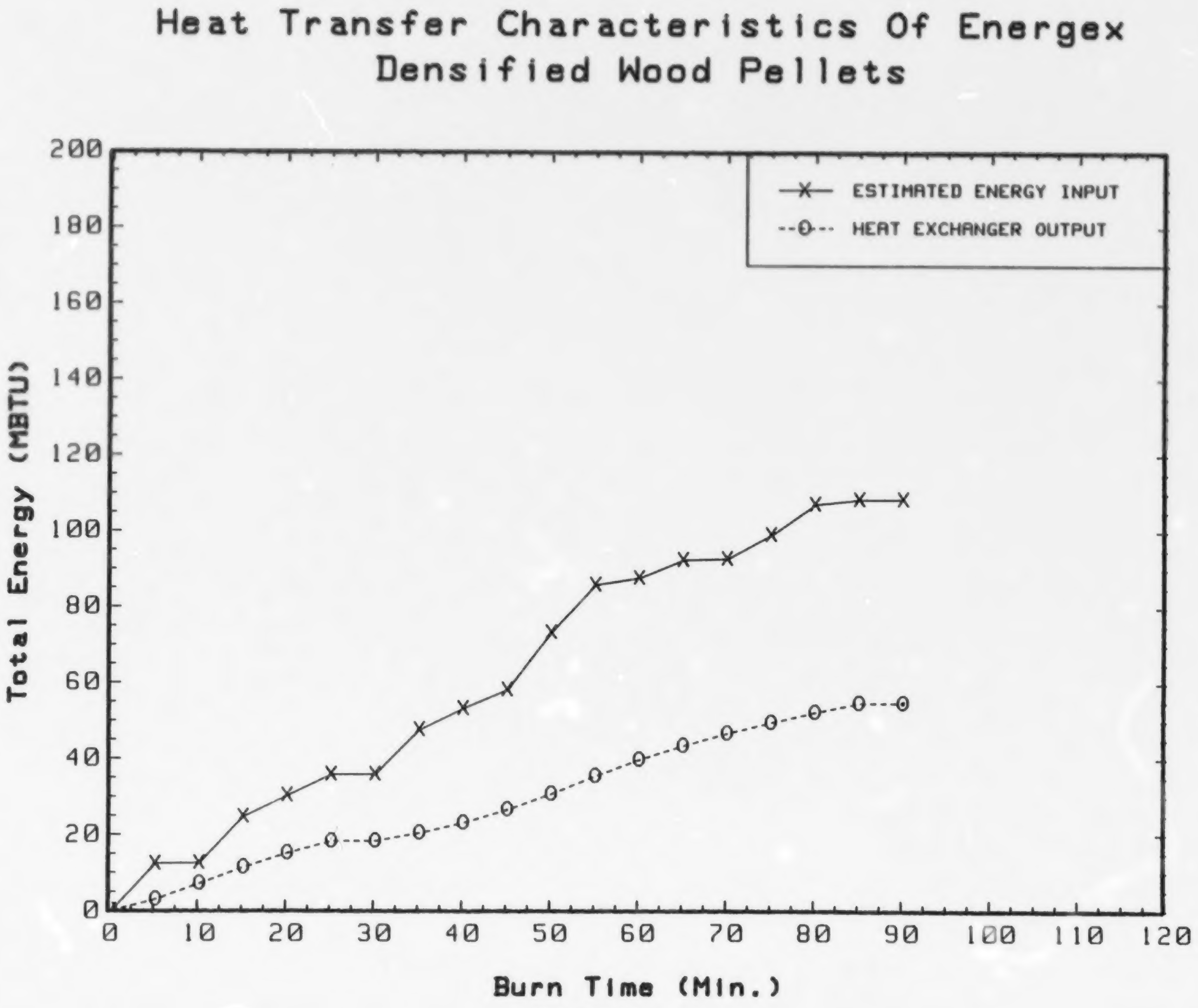

Heat Transfer Characteristics Of Energex Densified Wood Pellets
ESTIMATED ENERGY INPUT
HEAT EXCHANGER OUTPUT
Total Energy (MBTU)
200
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Burn Time (Min.)

FIGURE 19

Heat Transfer Characteristics Of 100% Pinewood Densified Wood Pellets

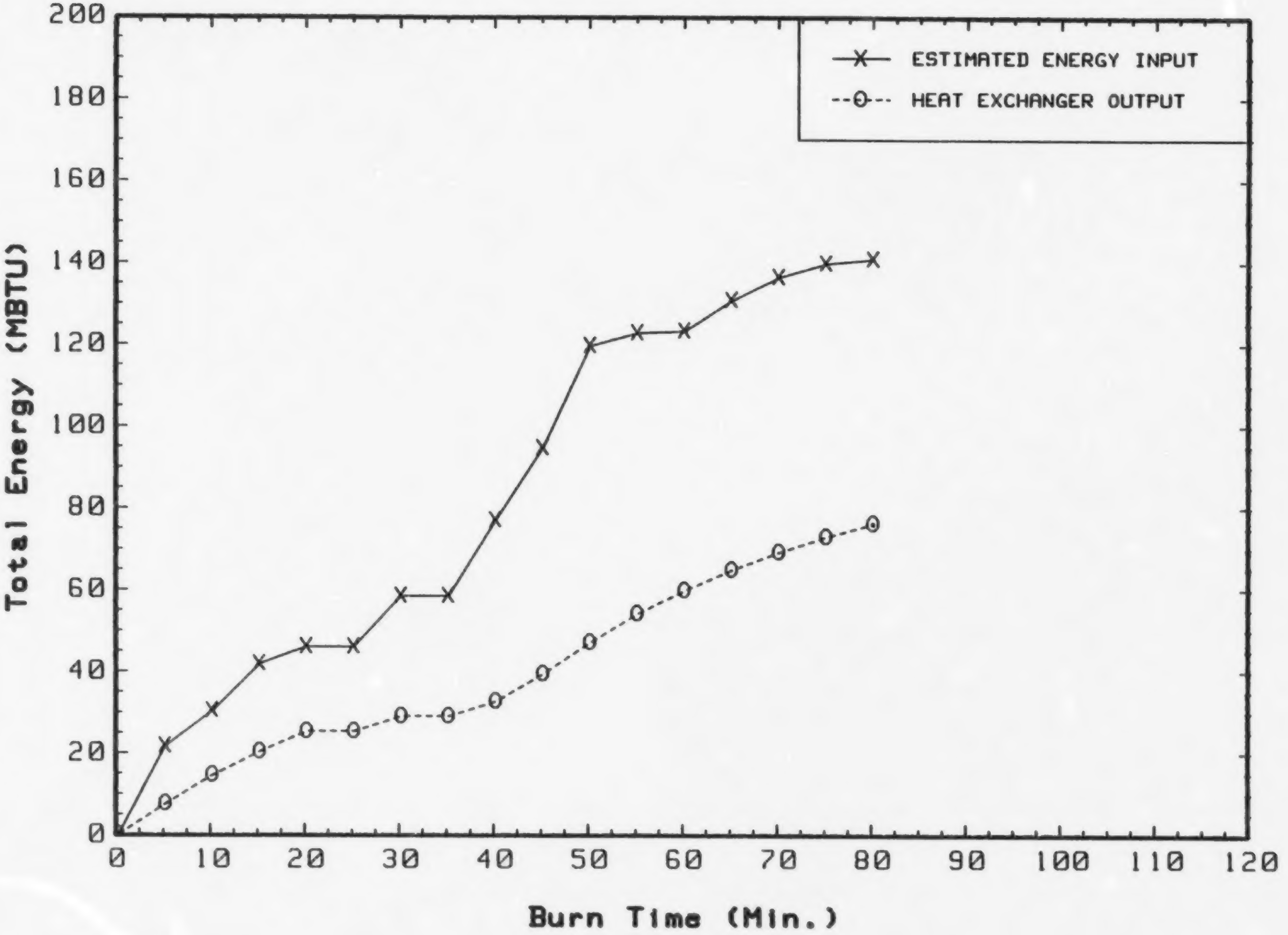


FIGURE 20

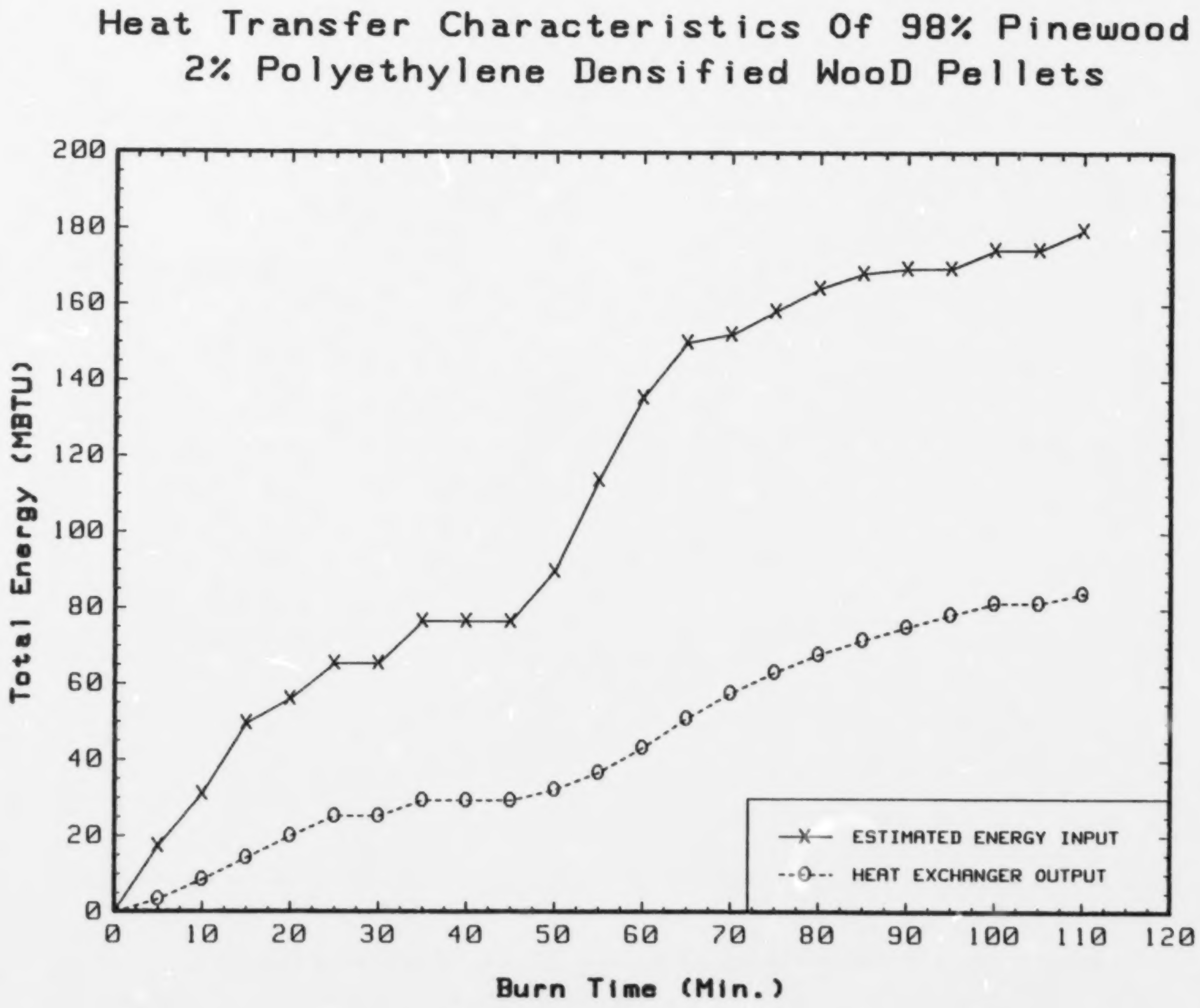

Heat Transfer Characteristics Of 98% Pinewood
2% Polyethylene Densified WooD Pellets
Total Energy (MBTU)
200
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Burn Time (Min.)
ESTIMATED ENERGY INPUT
HEAT EXCHANGER OUTPUT

FIGURE 21

Heat Transfer Characteristics Of 95% Pinewood
5% Polyethylene Densified Wood Pellets

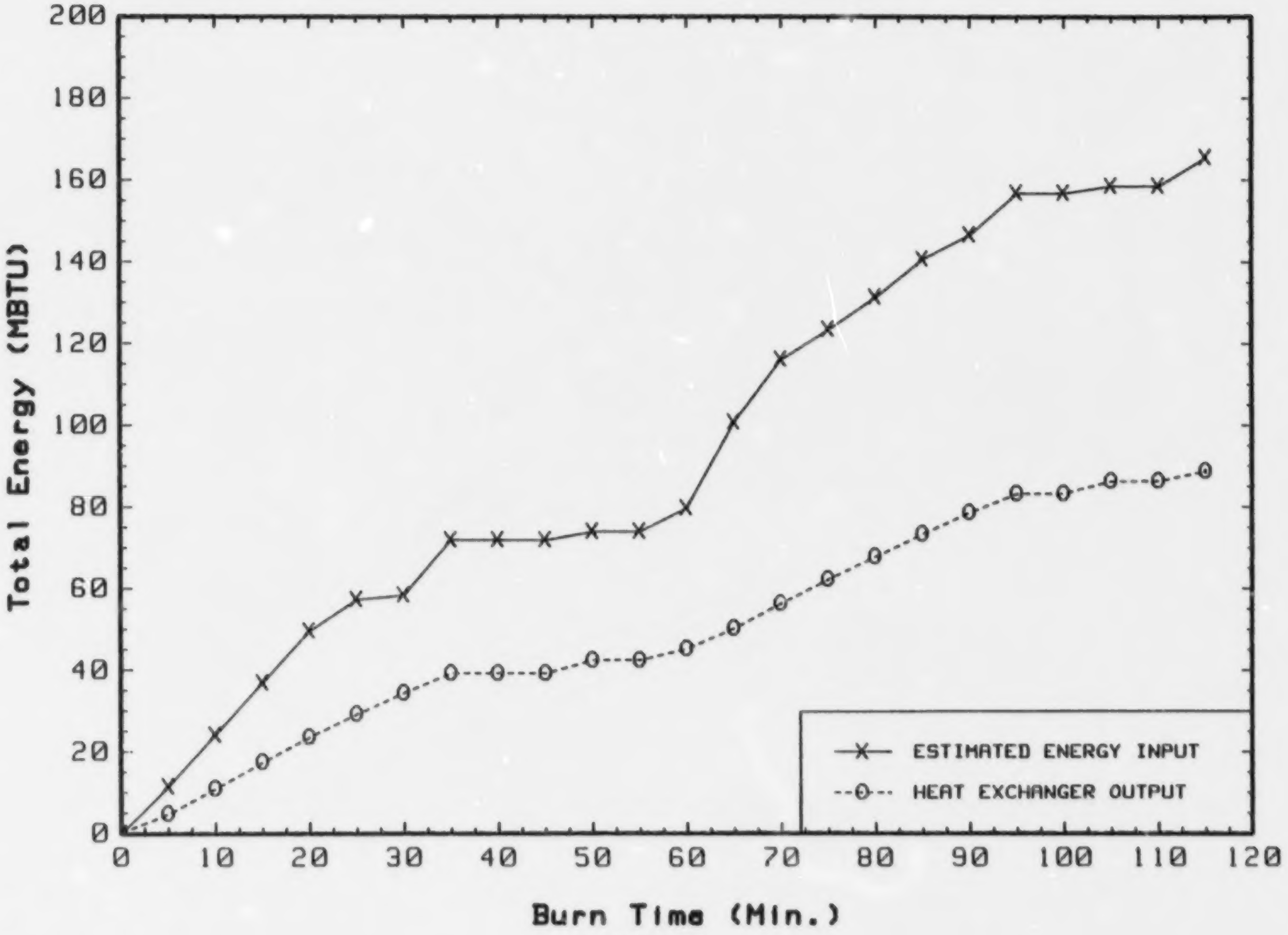


FIGURE 22

Table 1 - Comparative Characteristics of the Test Fuels

FUEL TYPE	DENSITY (Dry Basis) kg / m^3 (lb / ft^3)	MOISTURE CONTENT %		HEATING VALUE MJ / kg (Btu / lb)		ASH CONTENT %	
		DRY BASIS	AS-IS BASIS	DRY	AS-IS BASIS	3 CYCLE BURN TEST***	FUEL ANALYSIS
B ENERGEX*	1060** (66)**	9.6	8.8	17.7 (8483)	16.1 (7737)	4.83	3.92
C 100% PINE (jack)	1333 (83.2)	6.6		21.04 (9055)	19.65 (8457)	0.24	0.33****
D 98% PINE (jack) + 2% POLYETHYLENE	1300 (81.1)	8.7		21.67 (9325)	19.78 (8513)	0.1	0
E 95% PINE (jack) + 5% POLYETHYLENE	1271 (79.3)	6.8		22.2 (9522)	20.69 (8874)	0.24	0

* For more information on the "Energex" fuel see Table 2

** As-is basis

*** Based on the mass of fuel used, and analysis of coals after completion of testing of a given fuel.

**** No bark

(Source Bioshell Canada Ltd.)

CHARACTERISTICS	TYPICAL *		
DIMENSIONS	0.60 cm DIAMETER 1.90 cm LENGTH		
DENSITY	Bulk	Particle	
	0.65	1.06	
	40	66	
PROXIMATE ANALYSIS			
Moisture %	6.65	(8.79)**	(10.28)****
Ash	2.10	(3.92)**	(3.56)****
Volatiles	73.25		
Fixed Carbon	18.42		
	100.42		
ULTIMATE ANALYSIS (AS RECEIVED)			
Carbon (%)	48.31		
Hydrogen	5.60		
Sulphur	0.01		
Nitrogen	0.25		
Ash	2.10		
Oxygen	37.50		
	93.77 + 6.65 = 100.42		
HEAT VALUE (AS RECEIVED)			
MJ/kg	19.11		
BTU/lb	8216	(7737)**	(7688)***
NATURE OF ASH			
CaO (%)	40.61		
K_2O	5.03		
MgO	3.64		
SiO_2	28.34		
P_2O_5	1.68		
Fe_2O_3	3.01		
Mn_3O_4	1.23		
SO_3	1.06		
Al_2O_3	4.92		
Na_2O	0.99		
TiO_2	0.22		
BaO	0.24		
SrO	0.10		
L.o.F.	8.93		
	100.00		
ASH FUSIBILITY (REDUCING ATMOSPHERE)			
Initial (°C)	1240	2232°F	
Softening	1269	2284	
Hemispherical	1274	2293	
Fluid	1286	2315	

* AVERAGE OF EXISTING PLANTS (AUG. 1983) ** ORF Aug. 1985

***ORF March 1986

****ORF May 1986

TABLE 3

THE TIMES REQUIRED FOR IGNITION OF THE FIRST AND THE SECOND 4.5 KG. LOADS OF THE FOUR TYPES OF FUELS TESTED WITH AUXILLARY ENERGY OF AN IGNITION BURNER

	Fuel	Ignition Time (Minutes)	
		1st 10 lbs. load	2nd 10 lbs. load
B	Energex	2.3	0.5
C	100% Pine (Jack)	1.5	1.3
D	98% Pine (Jack) + 2% Polyethylene	0.7	0.2
E	95% Pine (Jack) + 5% Polyethylene	2.9	Nil

TABLE 4

Results of comparative combustion tests of commercial and improved biomass fuel pellets in the 150MJ Wood / Coal / Oil Furnace to establish trends in the overall fuel performance versus fuel type.

Test Fuels: A - Furnace fuel oil used at the beginning and at the end of the test program
B - 'ENERGEX' commercially available biomass fuel pellets - reference test
C - 100% pine (jack) - base test
D - 98% pine (jack) + 2% polyethylene
E - 95% pine (jack) + 5% polyethylene
} the best three of the improved pellets

PARAMETERS (Average of the last two of the three loads with each load = 4.5 kg)																
COMBUSTION								EMISSIONS							HEAT TRANSFER	
FUEL	BURN RATE kg/h	EXCESS AIR % (MIN)	ADIABATIC FLAME TEMP. °C (MAX)	STACK TEMP. °C	O_2 %	CO_2 % (MAX)	EFF. %	① CO PPM	② THC PPM	③ SO_2 PPM	④ NO_x PPM	⑤ PART. CONC. mg/M^3	PART. EMISSION RATE g/h	SUM*	HEAT OUTPUT MJ/h	EFF. %
A1	3.59	69***	1358	265	8.9	8.6	n/m	1.0	n/m	n/m	n/m	n/m	n/m	n/m	113	76 (76.2)**
A2	3.64	73***	1331	247	9.2	8.3	n/m	1.0	n/m	n/m	n/m	n/m	n/m	n/m	111	73.4 (76.5)**
B	5.73	372 (163)	568 (916)	181	16.8	4.2 (7.4)	66.0	1474	538	7.5	34	175	14	2228*	38.7	53.4
C	6.76	230 (48)	778 (1516)	222	14.9	6 (13.5)	84.5	1472	128	9.6	25	426	41	2061*	57.2	50.3
D	6.02	300 (76)	672 (1333)	215	15.7	5 (11.4)	91.1	1331	240	6.6	19	265	24	1861*	45.8	49.8
E	5.78	268 (101)	732 (1215)	212	15.6	5.2 (9.6)	89.7	1594	275	5.1	20	385	32	2279*	46.3	50.2

* Emission number was created for this study only and is a sum of parameters (1 + 2 + 3 + 4 + 5)
** Efficiency by the flue gas heat loss method
*** Based on O_2 reading
n/m not measured

TABLE 5

CHARGE AND BURN WEIGHTS ANALYSIS OF COMPARATIVE COMBUSTION TESTS OF WATER REPELLENT AND COMMERCIAL BIOMASS FUEL PELLETS

	FUEL	WEIGHTS INDICATED BY LOAD CELL IN POUNDS													
		1st 10 lb CYCLE				2nd 10 lb CYCLE				3rd 10 lb CYCLE				ACTUAL WEIGHTS OF COLLECTED COALS LBS. (ROUNDED TO 1st DEC.)	
		IN	OUT	COAL		IN	OUT	COAL		IN	OUT	COAL			
				LBS	MBTUS			LBS	MBTUS			LBS	MBTUS		MBTUS
B	ENERGEX (HHV = 7688 BTU/LB)	1084.5	1076.1	1.6	17.4	1086.1	1079.6	5.1	55.4	1089.8	1080.5	6	65.1	6.3	68.4
C	100% PINE (JACK) (HHV = 8459 BTU/LB)	1084.7	1075.8	1.1	15.1	1084.7	1076.2	1.5	20.5	1086.6	1076.8	2.1	28.7	2.4	32.8
D	98% PINE (JACK) + 2% POLYET. (HHV = 8516 BTU/LB)	1084.7	1075.7	1.0	13.9	1086.0	1076.6	1.9	26.5	1087.1	1075.8	1.1	15.3	1.1	15.3
E	95% PINE (JACK) + 5% POLYET. (HHV = 8903 BTU/LB)	1085.0	1076.3	1.3	17.8	1085.8	1076.4	1.4	19.1	1085.7	1076.6	1.6	21.9	1.4	19.1

H.H.V. OF COLLECTED COALS IN BTU/LB: ENERGEX = 10855; 100% PINE (JACK) = 13689; 98% PINE (JACK) + 2% POLYETHYLENE = 13947
(AT THE END OF THE 30 LB BURN TEST) 95% PINE (JACK) + 5% POLYETHYLENE = 13658

ASSUMING NO OTHER COMBUSTIBLES BESIDES CARBON AND WITH CARBON HAVING H.H.V. = 14,093 BTU/LB
COALS ASH CONTENT WILL BE:
ENERGEX
100% PINE (JACK) 23%
98% PINE (JACK) + 2% POL. 3%
95% PINE (JACK) + 5% POL. 1%
3%

THIS TRANSLATES INTO 4.83%, 0.24%, 0.1% AND 0.24% FUEL ASH CONTENT RESPECTIVELY.

MIXTURE OF SPRUCE AND JACK PINE SHAVINGS COLLECTED IN NORTHERN ONTARIO IN AUG. 1985 INDICATED 0.51% ASH

TABLE 6

Estimated Furnace Efficiency for the reference Energex fuel and the three jack pine fuels with and without polyethylene are computed for the last 4.5 kg. load cycle, for the last two 4.5 kg. load cycles and for the entire three 4.5 kg. load cycles. (This table was prepared to accentuate differences in the cold and hot start combustion characteristics of different fuels rather than the furnace efficiency.)

FUEL	% FURNACE EFFICIENCY (ESTIMATED)*		
	3rd 4.5 kg. cycle	COMBINED 3rd + 2nd 4.5 kg. cycles	COMBINED 3rd + 2nd + 1st 4.5 kg. cycles
Energex	48.7	50.5	35
100% Pine (Jack)	53.7	54.1	39.5
98% Pine (Jack) + 2% Polyethylene	47.3	46.8	41.7
95% Pine (Jack) + 5% Polyethylene	47.4	53.6	40.6

* Based on temperature rise and air flow measurements of air passing through test furnace heat exchanger and higher heating value of fuel pellets

TABLE 7 - ENERGEX PELLETS

Test No. 2
Fuel - Energex
Date - March 20, 1986

Time	O_2 %	CO_2 %	SO_2 PPM	CO PPM	NO_x PPM	THC PPM as CH_4
0	15.3	5.9	0.0	1046	45	508
5	13.7	7.3	1.8	753	64	319
10	15.1	5.8	1.3	915	50	340
15	16.6	4.3	1.4	905	39	360
20	17.8	3.2	1.8	1313	27	609
25	18.7	2.2	2.6	2096	18	925
30	18.6	2.7	4.4	3189	19	1486
35	15.8	5.2	8.7	1294	44	460
40	15.4	5.3	8.4	967	46	375
45	14.0	7.4	12.6	958	58	253
50	15.0	6.1	14.2	581	51	231
55	16.8	4.4	12.3	833	34	381
60	17.6	3.7	12.3	1256	26	441
65	17.9	3.2	11.3	1522	23	463
70	18.3	2.8	10.3	1659	21	449
75	18.6	2.5	10.4	2022	19	551
80	18.8	2.3	10.6	2533	17	737
85	18.9	2.1	10.8	2686	15	790
90						
Averages	16.8	4.2	7.5	1473.8	34.2	537.7

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 2.5 MINS. AND AVERAGED OVER 5 MIN. PERIODS DURING THE LAST TWO BURN CYCLES OF ENERGEX FUEL PELLETS IN THE TEST FURNACE

TABLE 8 - ENERGEX PELLETS

Start Time: 15:50

Stop Time: 17:20

	O_2 %	CO_2 %	SO_2 PPM	CO PPM	NO_x PPM	THC PPM	FLUE TEMP °F
0	16.0	5.1	-2.1	1407.5	37	654	273
5	13.7	7.3	1.4	727.6	63	331	424
10	14.8	6.1	1.4	873.9	52	332	470
15	16.2	4.6	1.3	889.0	42	347	433
20	17.6	3.3	1.4	991.3	29	525	380
25	18.1	2.8	2.5	1984.7	23	739	321
30	20.0	1.2	2.6	3878.0	6	2061	233
35	18.2	3.1	6.0	3573.0	23	1435	234
40	15.6	5.3	9.1	1124.4	46	406	360
45	15.5	5.2	8.0	1038.1	44	382	406
50	13.5	7.5	14.0	763.8	63	213	460
55	15.6	5.5	13.8	610.2	45	275	486
60	17.0	4.2	12.1	929.2	32	354	423
65	17.7	3.5	11.9	1312.1	25	468	367
70	18.1	3.0	11.0	1599.3	22	461	330
75	18.4	2.7	9.8	1732.7	20	466	304
80	18.6	2.4	10.5	2116.4	18	568	280
85	18.9	2.2	10.9	2676.4	16	789	261
90							

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 5 MINS. DURING THE LAST TWO BURNER CYCLES OF ENERGEX WOOD PELLETS IN THE TEST FURNACE

TABLE 9 - ENERGEX PELLETS

Start Time: 15:50

	Estimated Energy Input	Heat Exchanger Output
0	0	0
5	12.37	2.99
10	12.51	7.14
15	24.83	11.44
20	30.41	15.18
25	35.88	18.28
30	35.88	18.28
35	47.54	20.43
40	53.17	23.12
45	58.13	26.62
50	73.35	30.74
55	85.91	35.48
60	87.77	39.80
65	92.57	43.53
70	92.90	46.80
75	99.25	49.70
80	107.29	52.38
85	108.55	54.83
90	108.55	54.83
Total	1166.86	551.57

Average Efficiency 0.47

THE HEAT TRANSFER PARAMETERS COLLECTED
EVERY 5 MINS. DURING THE LAST TWO BURNER CYCLES
OF ENERGEX WOOD PELLETS IN THE TEST FURNACE

TABLE 10 - 100% PINEWOOD PELLETS

Test No. 3
Fuel - 100% Pinewood
Date - March 21, 1986

Time	O_2 %	CO_2 %	SO_2 PPM	CO PPM	NO_x PPM	THC PPM as CH_4
0	8.5	12.6	12	3060	50	298
5	12.6	8.3	10	970	37	75
10	15.1	5.8	7	735	27	49
15	16.6	3.3	6	675	21	34
20	17.1	3.7	4	757	19	25
25	18.3	2.4	4	845	10	19
30	19.5	1.6	3	3098	4	340
35	11.2	10.4	9	2865	38	379
40	7.7	13.5	26	3889	53	437
45	10.8	10.4	22	1775	41	140
50	14.0	6.9	16	678	29	64
55	15.7	5.2	11	507	22	42
60	16.7	4.1	8	544	18	40
65	17.6	3.3	7	696	13	31
70	18.3	2.6	4	979	9	29
75	19.0	1.9	4	1487	5	50
80						
Average	14.9	6	9.6	1472.5	24.75	128.3

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 2.5 MINS. AND AVERAGED OVER 5 MIN. PERIODS DURING THE LAST TWO BURN CYCLES OF 100% PINEWOOD PELLETS IN THE TEST FURNACE

TABLE 11 - 100% PINEWOOD PELLETS

Start Time: 14:25:00	Time is 30 seconds off synchronized with emissions, however they are averaged over 5 minute periods
Stop Time:	

	O_2 %	CO_2 %	SO_2 PPM	CO PPM	NO_x PPM	THC PPM	FLUE TEMP °F
0	7.6	13.4	8	3941	53	448	583
5	11.7	9.1	12	1070	41	85	629
10	14.7	6.1	7	750	28	53	533
15	16.2	4.6	6	667	23	36	463
20	17.1	3.7	4	745	18	27	410
25	18.0	2.6	4	754	14	19	377
30	19.4	1.5	3	2200	4	153	322
35	19.5	1.6	3	3996	4	527	231
40	8.8	12.8	12	3586	47	620	453
45	8.1	13.0	29	3781	51	258	581
50	11.5	9.4	20	1298	39	114	548
55	14.5	6.3	14	577	27	53	479
60	15.9	4.9	10	509	20	36	421
65	17.0	3.8	7	560	16	35	387
70	17.7	3.1	6	754	12	28	351
75	18.5	2.2	4	1107	7	30	314
80	19.0	1.8	3	1601	4	37	265
							432F
							222C

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 5 MINUTES DURING THE LAST TWO BURNER CYCLES OF 100% PINEWOOD PELLETS IN THE TEST FURNACE

TABLE 12 - 100% PINEWOOD PELLETS

	Estimated Energy Input MBTU	Heat Exchanger Output MBTU
0	0	0
5	21.75	7.58
10	30.46	14.62
15	41.94	20.41
20	46.11	25.39
25	46.11	25.39
30	58.53	29.06
35	58.53	29.06
40	77.07	32.73
45	94.74	39.48
50	119.66	47.20
55	122.82	54.21
60	123.34	59.94
65	130.80	64.93
70	136.47	69.30
75	139.86	73.05
80	140.92	76.25
Average	105.69	

Average Efficiency 54.1%

THE HEAT TRANSFER PARAMETERS COLLECTED
EVERY 5 MINS. DURING THE LAST TWO BURNER CYCLES
OF 100% PINEWOOD PELLETS IN THE TEST FURNACE

TABLE 13 - 98% PINEWOOD PELLETS

Test No. 4
Fuel - 98% Pinewood
Date - March 21, 1986

	4	4	4	4	4	4
Time	O_2	CO_2	SO_2	CO	NO_x	THC
	%	%	PPM	PPM	PPM	PPM as CH_4
0	19.6	1.5	4	200	4	38
5	12.4	8.5	6	1258	31	173
10	11.9	8.7	7	1301	35	152
15	12.9	7.5	7	1257	31	149
20	14.4	6.0	6	1081	25	111
25	15.2	5.3	5	915	23	74
30	16.4	4.0	5	789	20	33
35	18.1	2.4	3	822	10	5
40	18.9	1.8	2	2096	5	319
45	17.2	3.7	3	1937	13	403
50	13.5	7.3	4	1390	27	258
55	10.4	10.2	5	2577	40	907
60	9.5	10.7	16	3996	43	2038
65	12.9	7.5	20	2035	30	348
70	15.2	5.4	13	703	22	101
75	16.0	4.4	10	608	21	64
80	17.7	2.8	7	737	12	44
85	18.1	2.6	6	855	8	25
90	18.2	2.5	5	933	6	18
95	18.4	2.3	4	1047	4	13
100	18.7	2.1	4	1233	4	10
105	18.9	1.9	4	1519	3	8
Averages	15.7	5.0	6.6	1331.3	18.9	240.5

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 2.5 MIN. AND AVERAGED OVER 5 MINUTE PERIODS DURING THE LAST TWO BURN CYCLES OF 98% PINEWOOD PELLETS IN THE TEST FURNACE

TABLE 14 - 2% POLYETHYLENE

Start Time: 18:45

	O_2 %	CO_2 %	SO_2 PPM	CO PPM	NO_x PPM	THC PPM	FLUE TEMP °F
0	20.2	0.7	3	138	2	24	313
5	12.9	8.0	5	1115	28	161	533
10	11.9	8.7	7	1303	34	150	606
15	12.4	7.9	7	1397	32	161	592
20	14.1	6.2	6	1169	25	131	523
25	15.0	5.8	5	928	23	81	478
30	16.0	4.4	5	846	21	46	443
35	17.9	2.6	3	743	12	5	380
40	19.2	1.4	2	1836	4	234	288
45	18.0	2.8	2	2247	8	529	262.1
50	14.6	6.2	3	1446	22	277	383
55	11.2	9.3	4	1612	37	309	547
60	8.8	11.4	11	3996	45	2601	657
65	12.1	8.2	22	2797	33	484	581
70	14.9	5.6	14	739	23	114	472
75	15.8	4.7	10	622	22	69	428
80	17.3	3.1	8	685	14	49	399
85	18.1	2.6	6	885	8	29	339
90	18.1	2.5	5	901	6	19	322
95	18.3	2.3	4	1020	4	14	305
100	18.6	2.1	4	1151	4	11	286
105	18.8	1.9	4	1473	3	8	266
110	19.0	1.7	3	1698	3	5	251

420°F
215°C

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 5 MINS. DURING THE LAST TWO BURNER CYCLES OF 98% PINEWOOD PELLETS + 2% POLYETHYLENE IN THE TEST FURNACE

TABLE 15 - 2% POLYETHYLENE

Burn Time	Estimated Energy Input (MBTU)	Heat Exchanger Output (MBTU)
0	0	0
5	17.36	3.36
10	31.15	8.5
15	49.71	14.26
20	56.07	19.96
25	65.42	25.18
30	65.42	25.18
35	76.58	29.38
40	76.58	29.38
45	76.58	29.38
50	89.89	32.21
55	113.94	36.72
60	135.65	43.35
65	150.14	51.1
70	152.29	57.83
75	158.45	63.33
80	164.44	68.03
85	168.36	71.87
90	169.58	75.25
95	169.68	78.51
100	174.58	81.55
105	174.58	81.55
110	179.78	84.11
		45.8

THE HEAT TRANSFER PARAMETERS COLLECTED EVERY 5 MINS. DURING THE LAST TWO BURNER CYCLES OF 98% PINEWOOD PELLETS + 2% POLYETHYLENE IN THE TEST FURNACE

TABLE 16 - 95% PINEWOOD PELLETS

Test No. 5
Fuel - 95% Pinewood
Date - March 22, 1986

Time	O_2 %	CO_2 %	SO_2 PPM	CO PPM	NO_x PPM	THC PPM as CH_4
0	12.7	8.4	4	1549	29	290
5	11.1	9.5	7	3035	35	498
10	11.7	8.8	8	2409	34	359
15	12.8	7.6	8	1776	31	253
20	14.0	6.4	6	1116	26	142
25	15.1	5.6	6	1068	24	131
30	15.6	5.0	5	732	28	38
35	18.1	3.0	4	467	10	0
40	18.5	2.7	3	857	6	0
45	19.2	2.1	2	1546	5	416
50	19.2	2.3	2	2798	7	1699
55	12.9	8.3	4	2661	30	905
60	11.6	8.9	9	2897	34	538
65	12.9	7.8	9	1714	29	338
70	14.2	6.4	8	1213	27	198
75	14.9	5.7	6	960	27	117
80	15.9	4.7	5	983	24	95
85	17.4	3.4	4	888	19	22
90	18.9	2.2	3	1186	7	0
95	19.1	2.1	3	1403	5	0
100	19.2	2.0	3	1733	4	0
105	19.3	1.9	3	2073	3	0
110						
115						
Average	15.6	5.2	5.1	1593.8	20.2	274.5

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 2.5 MINS. AND AVERAGED OVER 5 MIN. PERIODS DURING THE LAST TWO BURN CYCLES OF 95% PINEWOOD PELLETS IN THE TEST FURNACE

TABLE 17 - 5% POLYETHYLENE

	O_2 %	CO_2 %	SO_2 PPM	CO PPM	NO_x PPM	THC PPM	FLUE TEMP °F
0	13.5	7.7	3	995	27	199	353
5	11.0	9.6	6	3083	35	528	532
10	11.5	9.0	8	2618	34	402	568
15	12.4	8.0	8	2054	32	308	545
20	13.8	6.6	6	1167	27	145	500
25	14.4	6.1	5	1065	25	138	454
30	15.3	5.4	6	1091	23	131	420
35	16.0	4.4	5	523	27	1	446
40	18.2	2.9	3	499	7	-19	392
45	18.6	2.6	2	1026	6	-21	336.8
50	19.3	1.9	2	1680	5	416	301.7
55	20.5	0.9	1	3314	2	2527	238
60	14.9	6.7	3	1374	23	517	354
65	11.3	9.2	8	3251	35	610	551
70	12.8	7.9	9	1692	29	339	535
75	13.7	6.9	8	1486	28	277	499
80	14.6	6.0	6	996	28	127	481
85	15.7	4.9	5	949	24	99	488
90	16.9	3.8	4	912	21	40	451
95	18.8	2.2	3	1117	8	-5	395
100	19.0	2.2	2	1254	6	-9	316
105	19.1	2.1	3	1479	4	-11	279
110	19.2	2.0	3	1807	4	-15	259
115	19.2	1.8	3	2275	3	-13	245.1
							413F
							212C

THE COMBUSTION AND EMISSION PARAMETERS COLLECTED EVERY 5 MINS. DURING THE LAST TWO BURNER CYCLES OF 95% PINEWOOD + 5% POLYETHYLENE PELLETS IN THE TEST FURNACE

TABLE 18 - 5% POLYETHYLENE

	Estimated Energy Input MBTU	Heat Exchanger Output MBTU
0	0	0
5	11.40	4.72
10	24.10	10.92
15	36.92	17.43
20	49.55	23.61
25	57.26	29.22
30	58.32	34.36
35	71.94	39.30
40	71.94	39.30
45	71.94	39.30
50	74.03	42.53
55	74.03	42.53
60	79.79	45.34
65	100.73	50.30
70	116.10	56.42
75	123.45	62.32
80	131.35	67.88
85	140.62	73.36
90	146.56	78.58
95	156.73	83.24
100	156.73	83.24
105	158.47	86.27
110	158.47	86.27
115	165.48	88.72
	=53.6%	46.3

THE HEAT TRANSFER PARAMETERS COLLECTED EVERY
5 MINS. DURING THE LAST TWO BURNER CYCLES OF 95% PINEWOOD
+ 5% POLYETHYLENE PELLETS IN THE TEST FURNACE

APPENDIX 1

SAMPLE COMPUTER PRINTOUT OF COMBUSTION TEST DATA SHEETS

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                      Ontario Research Foundation
                         Energy Systems Centre
                      Domestic Furnace Laboratory


Client        :
Subject       : Trial
Date          : 85/03/18
Description   : TEST OIL

General Data

   Test Number                          : 000
   Record Number                        : 000
   Time                                 : 12:55:00
   Fuel      - Type                     : No. 2 Oil
             - Heating Value            :  45566 kJ/kg      19590 Btu/lb
   Room Air  - Dry Bulb Temp.           :   20.4 deg C       68.7 deg F
             - Dewpoint Temp.           :    1.7 deg C       35.1 deg F
             - Barometric Pres.         : 101.94 kPa        30.19 in.Hg

Combustion Data

   Chamber Temperature                  :   70.1 deg C      158.2 deg F
   Fuel Mass                            :  14.60 kg         32.18 lbs
   Fuel Input - Mass Rate               :   3.56 kg/hr       7.86 lbs/hr
              - Total Mass              :   6.74 kg         14.86 lbs
              - Energy Rate             : 162398 kJ/hr     153924 Btu/hr
              - Total Energy            : 307.16 MJ        291.13 MBtu

Heat Exchanger Data

   Air Entering   - Dry Bulb Temp.      :   25.7 deg C       78.2 deg F
                  - Dewpoint Temp.      :    1.7 deg C       35.1 deg F
   Air Leaving    - Dry Bulb Temp.      :   71.5 deg C      160.7 deg F
                  - Dewpoint Temp.      :    1.7 deg C       35.1 deg F

   Air Flow Rate  - Actual Volume       :  37.96 m^3/min     1341 ft^3/min
                  - Standard Volume     :  37.42 m^3/min     1322 ft^3/min
                  - Actual Mass         :   2698 kg/hr       5947 lbs/hr
                  - Dry Mass            :   2686 kg/hr       5922 lbs/hr
   Heat Transfer  - Rate                : 124877 kJ/hr     118361 Btu/hr
                  - Total               : 164.48 MJ        155.89 MBtu

Flue Gas Data

   Temperature                          :  266.2 deg C      511.2 deg F
   Smoke Number                         :      1
   Carbon Monoxide                      :      1 ppm
   Carbon Dioxide                       :    8.6 %
   Oxygen                               :    8.8 %
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                         Ontario Research Foundation
                           Energy Systems Centre
                         Domestic Furnace Laboratory

Client      : DSS
Subject     : ENERGEX PELLETS
Date        : 85/03/20
Description :
ENERGEX PELLET TEST

General Data

   Test Number                       : 002
   Record Number                     : 013
   Time                              : 16:10:00
   Fuel      - Type                  : Solid Fuel
             - Heating Value         :  17996 kJ/kg       7737 Btu/lb
   Room Air  - Dry Bulb Temp.        :   10.2 deg C       50.4 deg F
             - Dewpoint Temp.        :    2.7 deg C       36.8 deg F
             - Barometric Pres.      : 101.10 kPa        29.94 in.Hg

Combustion Data

   Chamber Temperature               :  238.5 deg C      461.3 deg F
   Fuel Mass                         : 490.01 kg       1080.29 lbs
   Fuel Input - Mass Rate            :   3.93 kg/hr       8.66 lbs/hr
              - Total Mass           :   5.69 kg         12.55 lbs
              - Energy Rate          :  70693 kJ/hr      67004 Btu/hr
              - Total Energy         : 102.48 MJ         97.13 MBtu

Heat Exchanger Data

   Air Entering   - Dry Bulb Temp.   :    11.8 deg C      53.2 deg F
                  - Dewpoint Temp.   :     2.7 deg C      36.8 deg F
   Air Leaving    - Dry Bulb Temp.   :    28.3 deg C      82.9 deg F
                  - Dewpoint Temp.   :     2.7 deg C      36.8 deg F

   Air Flow Rate  - Actual Volume    :   38.41 m^3/min    1356 ft^3/min
                  - Standard Volume  :   39.38 m^3/min    1391 ft^3/min
                  - Actual Mass      :    2839 kg/hr      6258 lbs/hr
                  - Dry Mass         :    2826 kg/hr      6229 lbs/hr
   Heat Transfer  - Rate             :   47349 kJ/hr     44878 Btu/hr
                  - Total            :   45.67 MJ        43.29 MBtu

Flue Gas Data

   Temperature                       :   193.1 deg C     379.6 deg F

   Carbon Monoxide                   :     962 ppm
   Carbon Dioxide                    :     5.6 %
   Oxygen                            :    16.1 %
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                   Ontario Research Foundation
                     Energy Systems Centre
                   Domestic Furnace Laboratory

Client        : DSS
Subject       : NO PE
Date          : 85/03/21
Description   :
100% PINE WOOD NO POLYETHYLENE

General Data

   Test Number                         : 003
   Record Number                       : 000
   Time                                : 15:10:00
   Fuel      - Type                    : Solid Fuel
             - Heating Value           :  19676 kJ/kg      8459 Btu/lb
   Room Air  - Dry Bulb Temp.          :    6.5 deg C      43.7 deg F
             - Dewpoint Temp.          :    2.7 deg C      36.8 deg F
             - Barometric Pres.        : 102.89 kPa       30.47 in.Hg

Combustion Data

   Chamber Temperature                 :  344.1 deg C     651.4 deg F
   Fuel Mass                           : 490.91 kg      1082.28 lbs
   Fuel Input - Mass Rate              :  11.37 kg/hr     25.07 lbs/hr
              - Total Mass             :   8.93 kg        19.68 lbs
              - Energy Rate            : 223717 kJ/hr    212042 Btu/hr
              - Total Energy           : 175.66 MJ       166.50 MBtu

Heat Exchanger Data

   Air Entering  - Dry Bulb Temp.      :   12.5 deg C      54.5 deg F
                 - Dewpoint Temp.      :    2.7 deg C      36.8 deg F
   Air Leaving   - Dry Bulb Temp.      :   42.1 deg C     107.8 deg F
                 - Dewpoint Temp.      :    2.7 deg C      36.8 deg F

   Air Flow Rate - Actual Volume       :  38.14 m^3/min    1347 ft^3/min
                 - Standard Volume     :  39.69 m^3/min    1402 ft^3/min
                 - Actual Mass         :   2861 kg/hr      6308 lbs/hr
                 - Dry Mass            :   2848 kg/hr      6279 lbs/hr
   Heat Transfer - Rate                :  85445 kJ/hr     80986 Btu/hr
                 - Total               :  73.08 MJ        69.27 MBtu

Flue Gas Data

   Temperature                         :  305.2 deg C     581.4 deg F

   Carbon Monoxide                     :   1432 ppm
   Carbon Dioxide                      :   12.7 %
   Oxygen                              :    4.5 %
```

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                         Domestic Furnace Laboratory

Client       : DSS
Subject      : 2% PE
Date         : 85/03/21
Description :
PINE WOOD 2% POLYETHYLENE

General Data

   Test Number                          : 003
   Record Number                        : 034
   Time                                 : 19:10:01
   Fuel       - Type                    : Solid Fuel
              - Heating Value           :  19808 kJ/kg        8516 Btu/lb
   Room Air - Dry Bulb Temp.            :    6.0 deg C        42.8 deg F
              - Dewpoint Temp.          :   -1.9 deg C        28.5 deg F
              - Barometric Pres.        : 102.65 kPa         30.40 in.Hg

Combustion Data
   Chamber Temperature                  :  505.7 deg C       942.3 deg F
   Fuel Mass                            : 488.70 kg        1077.40 lbs
   Fuel Input - Mass Rate               :   5.98 kg/hr       13.18 lbs/hr
                - Total Mass            :   7.30 kg          16.09 lbs
                - Energy Rate           : 118416 kJ/hr      112237 Btu/hr
                - Total Energy          : 144.53 MJ         136.99 MBtu

Heat Exchanger Data

   Air Entering   - Dry Bulb Temp.      :   12.4 deg C        54.3 deg F
                  - Dewpoint Temp.      :   -1.9 deg C        28.5 deg F
   Air Leaving    - Dry Bulb Temp.      :   35.4 deg C        95.7 deg F
                  - Dewpoint Temp.      :   -1.9 deg C        28.5 deg F

   Air Flow Rate - Actual Volume        :  38.06 m^3/min      1344 ft^3/min
                 - Standard Volume      :  39.57 m^3/min      1397 ft^3/min
                 - Actual Mass          :   2852 kg/hr        6288 lbs/hr
                 - Dry Mass             :   2843 kg/hr        6268 lbs/hr
   Heat Transfer - Rate                 :  66099 kJ/hr       62650 Btu/hr
                 - Total                :  36.21 MJ          34.32 MBtu

Flue Gas Data

   Temperature                          :  247.6 deg C       477.6 deg F

   Carbon Monoxide                      :    919 ppm
   Carbon Dioxide                       :    7.9 %
   Oxygen                               :   12.8 %
```

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                           Energy Systems Centre
                         Domestic Furnace Laboratory


Client      : DSS
Subject     : 5% PE
Date        : 85/03/22
Description :
PINE WOOD 5% POLYETHYLENE

General Data

   Test Number                        : 005
   Record Number                      : 072
   Time                               : 12:55:01
   Fuel      - Type                   : Solid Fuel
             - Heating Value          :  20694 kJ/kg        8897 Btu/lb
   Room Air  - Dry Bulb Temp.         :   12.1 deg C        53.8 deg F
             - Dewpoint Temp.         :   -1.9 deg C        28.5 deg F
             - Barometric Pres.       : 102.72 kPa         30.42 in.Hg

Combustion Data

   Chamber Temperature                :  436.7 deg C       818.0 deg F
   Fuel Mass                          : 490.30 kg        1080.94 lbs
   Fuel Input - Mass Rate             :   9.41 kg/hr       20.74 lbs/hr
              - Total Mass            :   9.46 kg          20.85 lbs
              - Energy Rate           : 194675 kJ/hr      184516 Btu/hr
              - Total Energy          : 195.70 MJ         185.48 MBtu

Heat Exchanger Data

   Air Entering   - Dry Bulb Temp.    :   16.8 deg C        62.3 deg F
                  - Dewpoint Temp.    :   -1.9 deg C        28.5 deg F
   Air Leaving    - Dry Bulb Temp.    :   44.2 deg C       111.6 deg F
                  - Dewpoint Temp.    :   -1.9 deg C        28.5 deg F

   Air Flow Rate - Actual Volume      :  38.06 m^3/min      1344 ft^3/min
                 - Standard Volume    :  38.98 m^3/min      1377 ft^3/min
                 - Actual Mass        :   2810 kg/hr        6195 lbs/hr
                 - Dry Mass           :   2801 kg/hr        6176 lbs/hr
   Heat Transfer - Rate               :  77514 kJ/hr       73469 Btu/hr
                 - Total              :  99.77 MJ          94.56 MBtu

Flue Gas Data

   Temperature                        :  279.4 deg C       534.9 deg F

   Carbon Monoxide                    :   1432 ppm
   Carbon Dioxide                     :   11.5 %
   Oxygen                             :    7.6 %
```

APPENDIX 2

COMBUSTION EFFICIENCY DETAILED CALCULATIONS

Calculation of the Furnace Combustion Efficiency

Furnace combustion efficiencies for the five test fuels are based on the following respective test data obtained from Tables 1, 2, 5 and 6.

	Carbon in the coals quenched after 3 cycles %	Carbon Monoxide Av of 2nd & 3rd Cycles PPM	THC Av of 2nd & 3rd Cycles PPM
Fuel A - #2 Fuel Oil			
B - Energex	77	1474	538
C - 100% Pine (Jack)	97	1472	128
D - 98% Pine (Jack) + 2% Polyethylene	99	1331	240
E - 95% Pine (Jack) + 5% Polyethylene	97	1594	275

Combustion Efficiency = Fuel H.H.V.-("C"Loss+CO_{Loss}+THC_{Loss})x100%÷Fuel H.H.V.

Carbon heat loss = (% ash /(1 - $\frac{\text{\% Carbon ash}}{100}$) x % carbon in ash/100 x HHV/100

HHV = Fuel High Heating Value

Carbon loss BTU/lb (fuel)

Fuel	
B	2279
C	1094
D	512
E	638

$$\text{CO loss} = \frac{\text{\%CO x Carbon heating value x ((\% Carbon in fuel/100)-X))}}{\text{\%CO}_2 + \text{\%CO}}$$

Carbon Monoxide loss BTU/lb (fuel)

Fuel	
B	143
C	142
D	169
E	192

Total Hydrocarbon (THC) Losses

$$\text{THC}_{\text{Loss}} = \text{PPM (THC)} \times 1 \times 10^{-6} \times \text{SCF (flue gas/lb fuel)} \times \text{HHV (Methane)}$$

THC is assumed to be methane having HHV of 1013.2 BTU/scf

Lbs. of flue gas per lb. of fuel burned is as follows:

Fuel B	26.43
C	20.45
D	24.42
E	23.06

Assuming flue gas density to be as that of air, i.e. 0.076 lb/ft^3 then volumes of flue gas produced in Std. Cu. Ft. (SCF) per lb. of fuel burned are as follows:

Fuel B	347.8
C	269.0
D	321.3
E	303.4

THC Loss BTU/lb. (fuel)

Fuel B = 190
C = 35
D = 78
E = 85

Combustion Efficiency %

Fuel B = 66.0
C = 84.5
D = 91.1
E = 89.7